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DOCUMENT CHANGE RECORD

Issue	*Date*	*Changes and Reasons*
1 Draft A	5th August 2002	Draft for internal review and comment by SOS/ESYS
1	8th August 2002	Updates in response to comments, including: – explicitly listed co-authors on front page – increased page margins slightly – included a summary of overall study objectives in §1.2 – included an introductory paragraph in §2.1 outlining how altimeters estimate currents – reimported Table 2-1 to improve legibility – modified the discussion of XTI formation issues in §3.3.1 – changed title of §3.5 to be clearer – corrected some cross-references – corrected link budget equation in §A.2.1 – various other minor clarifications and typos throughout

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LIST OF ACRONYMS

aka	also known as
AOCS	Attitude and Orbit Control System
ATI	Along-Track Interferometry
ATSR	Along-Track Scanning Radiometer
BNSC	British National Space Centre
CNES	Centre National d'Etudes Spatiales
COTS	Commercial Off The Shelf
DLR	Deutsche Zentrum für Luft- und Raumfahrt
DORIS	Determination d'Orbite et Radiopositionement Integre par Satellite
EMC	Electro-Magnetic Compatibility
FFT	Fast Fourier Transform
FM	Frequency Modulation
GEO	Geostationary Earth Orbit
GPS	Global Positioning System
HPA	High Power Amplifier
LAN	Local Area Network
LED	Light Emitting Diode
LEO	Low Earth Orbir
LNA	Low Noise Amplifier
MEO	Middle Earth Orbit
MTI	Moving Target Indicator
PRF	Pulse Repetition Frequency
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval (= 1 / PRF)
RAL	Rutherford Appleton Laboratory
RAR	Real Aperture Radar
ROM	Rough Order of Magnitude
SAR	Synthetic Aperture Radar
SEA	Systems Engineering & Assessment Ltd
SMS	Service Mission Support
SNR	Signal-to-Noise Ratio
SOS	Satellite Observing Systems Ltd
SRTM	Shuttle Radar Topography Mission
SST	Sea Surface Temperature
SSTL	Surrey Satellite Technology Ltd
T/R	Transmit/Receive
TV	Television
WP	Work Package
XTI	Across-Track Interferometry

1 INTRODUCTION

1.1 BACKGROUND

This document was prepared by Systems Engineering & Assessment Ltd (SEA) as part of a team lead by Satellite Observing Systems Ltd (SOS). This technical note refers to Work Package 33, “Technical Comparison of Candidate Systems” of the study “Ocean Currents from Space”. The overall study is performed under the British National Space Centre (BNSC) Service Mission Support (SMS) Programme. The proposal [1] refers.

1.2 OBJECTIVES OF THIS WORK PACKAGE

The overall study considers the viability of a commercial satellite Service Mission to measure ocean currents. Work Packages 1 and 2 considered the applications of and market for ocean current measurements. Various applications were identified and their requirements (in terms of accuracy, spatial resolution, update rate etc.) were characterised; these requirements span a wide range.

Work Package 3, of which this technical note forms a part, characterises candidate systems to address the various application requirements, as an input into the overall trade-offs to be performed in Work Package 4. The current work package does not perform those trade-offs, although it obviously needs to restrict consideration to those concepts that might perhaps be relevant.

For each candidate system/concept, the characterisation includes the following aspects (where appropriate):

– the concept and physical principles;
– the nature and accuracy of the measurements and their inversion to ocean currents;
– any spin-offs, in terms of any additional useful information provided (e.g. wave heights);
– spatial and temporal coverage / resolution;
– implementation issues including payload complexity/mass/power/maturity, requirements for orbit / attitude control / knowledge, data-handling and comms, implications of these for the bus and feasibility of a small-satellite solution, typical instrument/spacecraft/mission;
– available technology trade-offs of costs and performance;
– a summary of the key issues, benefits, risks, developments required.

WP33 focuses on active sensors. Passive sensors, e.g. radiometers similar to ATSR, are also potentially useful for observations of current flows and patterns. Passive sensors are not covered in this work package or document, but were addressed separately in WP32 by RAL [2].

1.3 STRUCTURE OF THIS DOCUMENT

The main text of this document is arranged by the sensor type. The classification of candidate system types into generic categories is as logical as possible, but is necessarily somewhat arbitrary because of the overlap between categories. Broadly:

- §2, "Conventional and Advanced Altimeters" covers nadir-looking (and specular bistatic) active instruments. This includes nadir-looking systems employing interferometric and/or synthetic aperture techniques, but not parasitic radars.
- §3, "Interferometric Radars" covers side-looking active instruments employing multiple antennas to provide information on surface height or velocity. This category includes both real aperture and synthetic aperture radars.
- §4, "Parasitic Radars" covers systems that do not have their own transmitter but instead exploit third-party transmissions. These might operate as either an altimeter or an interferometric radar. One particular promising parasitic radar option, viz. GPS altimetry, is covered in more detail in a separate document prepared by SSTL [3].
- §5 presents summary conclusions concerning the various technology options.

In principle, both along-track interferometry or across-track interferometry, discussed in §3, could be performed using space-based Synthetic Aperture Radar (SAR) or Real Aperture Radar (RAR). The radar instrument aspects are deferred to annexes:

- Annex A provides "An Illustrative Real Aperture Radar Design". While the resolution of a RAR is very limited, the instrument is modest and a RAR is likely to be compatible with a small-satellite implementation.
- For comparison, Annex B provides "An Illustrative Synthetic Aperture Radar Design". A SAR might well be better for interferometry applications, but is much more demanding (in terms of mass, power and data-rate) and is unlikely to be compatible with a small satellite.

These annexes also include a useful summary of the spatial/temporal coverage of such systems.

2 CONVENTIONAL AND ADVANCED ALTIMETERS

2.1 CONVENTIONAL RADAR ALTIMETERS

2.1.1 Introduction

Space-based conventional radar altimeters have proved to be useful for observing the ocean including, indirectly, measuring ocean currents [4]. Altimeters make accurate measurements of the sea surface height, and hence the sea surface slope. This determines the horizontal pressure gradients that drive geostrophic currents in the open ocean. Geostrophic currents are only one component of ocean currents but give a good approximation to the total current in regions where friction forces can be neglected, i.e. away from the coast, the sea surface (where wind effects can be significant) and the sea floor. In fact, since the geoid (the level at which the sea surface would sit in the absence of currents) is not precisely known, altimeters only measure geostrophic velocity anomalies based on the deviation from the mean sea level over numerous passes. However, absolute velocity anomalies from altimetry are expected to become available in the next few years following two precise gravimetric missions, GRACE and GOCE, designed to measure the geoid much more accurately.

The technology is well established and a succession of missions, such as Topex/Poseiden, ERS RA, Jason-1, etc., has been and continues to be operated. Generally, these are large scientific missions and we would be unlikely to propose launching such systems specifically for commercial SMS use. However…

- It is clearly desirable to exploit any available third-party altimetry information.
- Radar altimeters provide an obvious benchmark for the performance of alternative concepts.
- Radar altimeters are also potentially useful for calibrating alternative concepts.

Hence, a short discussion of conventional radar altimeters is provided below. This also provides some background to support later subsections.

2.1.2 Typical Instrument

The first modern radar altimeter is generally considered to be the one flown on Seasat, and most later instruments have followed the same basic principles. A detailed description of the principles of radar altimetry is out of the scope of the current document, but it may be helpful to include a brief summary of the concept. The following paragraphs have been derived from the excellent summary of the RA-2 instrument at http://Envisat.estec.esa.nl/instruments/ra2.

The range resolution of the altimeter is about half a metre, corresponding to a temporal resolution of 3.125 ns. A resolution of 3.125 ns may be achieved using a short pulse of this duration; this approach is used in some Ultra-Wide-Band radars and in laser radar. The engineering difficulties involved in achieving the required peak power mean that normally a chirped approach is used.

The approach traditionally used in radar systems is to inject a short impulse into a dispersive delay line, which spreads the energy over time, generating a frequency-modulated or chirp signal. Newer systems may use direct digital synthesis (and frequency multiplication for higher bandwidths) at base-band followed by up-conversion. When the echo is received, such a radar passes the signal through an inverse matched filter which compresses the chirp signal back to a short pulse. This technique is called pulse compression. The compressed time resolution is inversely proportional to the chirp bandwidth.

Generation of transmit chirps is not the most difficult technical challenge. Production of a matched receive dispersion (especially if frequency multiplication has been used in the transmit chain) is much more difficult. A deramp technique is therefore used in combination with linear FM pulse modulation.

The return echo signal consists of many discrete chirps, each reflected from a different facet of the ocean surface, with slightly different delay times. The full-deramp concept consists of mixing this incoming signal with a replica of the transmitted chirp, slightly shifted and extended in frequency. The deramp mixer generates signals which are the difference frequency between its two inputs. As the two inputs have the same rate of change of frequency, the output frequencies are constant tones. The input signals are linear so there is a mapping of time offset into frequency offset. As a result, targets with a different range will give echoes at different frequencies. Therefore, the range discriminator can be implemented with a bank of contiguous filters. The translation from the time domain to the frequency domain simplifies the signal processing stages as they can work with much-reduced bandwidth.

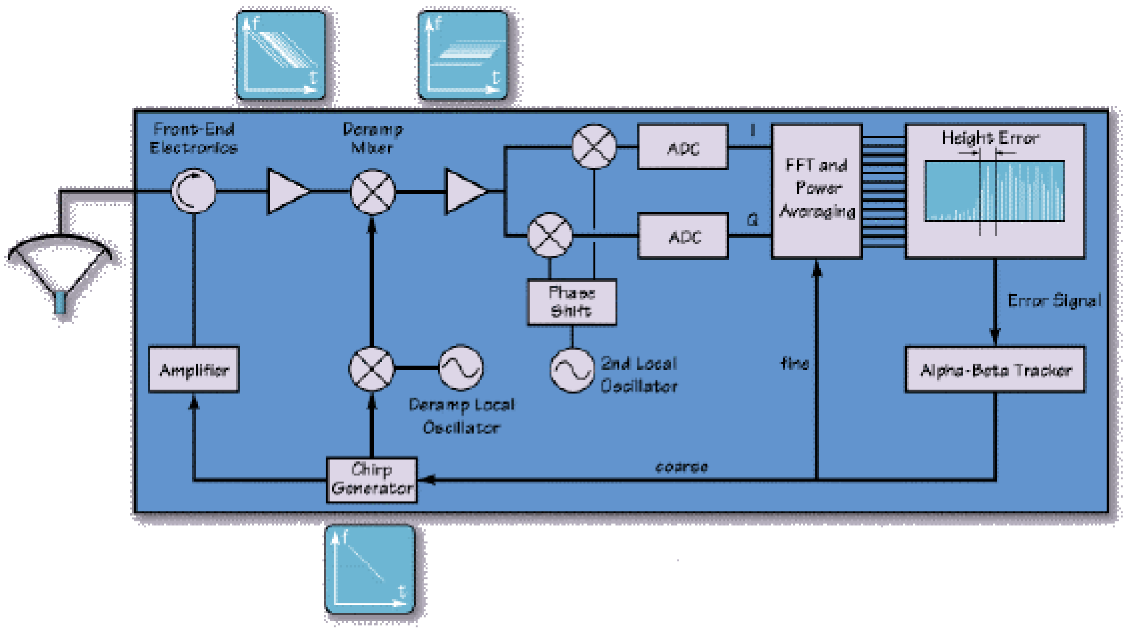

Figure 2-1. Block Diagram of RA-2 (single channel only shown)

Because the downlink data comprises the (time averaged) echo pulse shapes, it is possible also to extract wave height and wind speed parameters from the shape of the leading and trailing edges, and these products have value in their own right.

2.1.3 Instrument Budgets and Performance

The RA-2 altimeter has a mass of 110 kg, a power demand of 110 W, and generates a data stream of 100 kbps. The operational duty cycle is 100%.

The primary parameter measured by a radar altimeter is the range to the surface. The range resolution of the altimeter is about half a metre but the range measurement performance over the ocean is about one order of magnitude better than this. This is achieved by fitting the shape of the sampled echo waveform to a model function that represents the form of the echo, and by averaging.

In order to deduce the surface altitude, additional information is required, viz.

- the position of the spacecraft;
- the deviation of the speed of light (at the altimeter frequency) from the vacuum value.

These aspects contribute significantly to the overall error budget.

Several systems have been used to determine the spacecraft position. Laser ranging from ground stations and high order GPS processing are both used, but for most missions to date the DORIS system is the prime mechanism. Absolute accuracies of a few centimetres have been achieved, with 1 cm the goal.

The dry atmosphere contributes a range bias of the order of several metres, but this is not difficult to model and compensate. The refractive index depends also on atmospheric humidity, which can contribute up to ~10 mm. This can be modelled and partially compensated if the water vapour column amount is known or estimated, preferably from separate radiometer measurements or, failing that, from climate data. Ionospheric effects are much more serious for a single-frequency altimeter, but can be determined and removed by simultaneous operation at two frequencies.

Table 2-1 summarises the typical error budgets for RA-2. (Note that Envisat uses the ISS system for orbit determination, and the orbit errors are quite large. For dedicated altimetry missions, using laser ranging / DORIS / GPS, the errors would be much smaller).

Signal or Error source	*Length (km)*	*Height (cm)*	*Slope (µrad)*	*Mission-avg. slope (µrad)*
Gravity Signal	12–400	1–300	1–300	1–300
Measurement error sources:				
Orbit errors [1]	8000–20,000	400–1000	< 0.5	< 0.2
Ionosphere [2,3]	> 900	20	< 0.22	< 0.1
Wet Troposphere [4]	> 100	3-6	< 0.6	< 0.3
Sea-state bias [5]	> 20	< 0.6	< 0.3	< 0.1
Inverse barometer [6]	> 250	< 5	< 0.2	< 0.1
Oceanographic error sources:				
Basin-scale circulation (steady) [7]	> 1000	100	< 1	< 1
El Niño [8] , inter-annual variability, planetary waves	> 1000	20	< 0.2	< 0.1
Deep ocean tide model errors [4,10]	> 1000	3	< 0.03	< 0.01
Coastal tide model errors [3,10]	50–100	< 13	< 2.6	< 1.1
Eddys & Mesoscale Variability [9]	60–200	30–50	2.5–5	1–2
Meandering jet (Gulf Stream) [7,11]	100–300	30–100	3–10	2–4
Steady Jet (Florida Current) [7,11]	100	50–100	5–10	5–10

[1]Dynamic orbit determination using the ISS SIGI system, considering errors in force, measurement, attitude, center of mass, and effect of EXPRESS nadir pallet moment arm. [2]Imel [1994] [3]Yale [1997] [4]Chelton et al. [2001] [5]Monaldo [1998] [6]Ponte [1994] [7]Fu & Chelton [2001] [8]Picaut & Busalacchi [2001] [9]LeTraon & Morrow [2001] [10]Shum et al. [2001] [11]Smith & Sandwell [1995].

Table 2-1. Contributions to Errors in Sea Surface Height and Slope [5]

Much attention is given to orbit selection. ERS and Envisat are in sun synchronous orbits to meet the operational needs of the other instruments on the spacecraft (including the power and thermal design and the illumination constrains of optical and IR sensors). Dedicated altimetry satellites such as Topex/Poseidon and Jason-1 are in non-sun-synchronous orbits, selected to minimise aliasing of solar tides into altimetry measurements.

Because the altimeter return is pulse limited rather than beam limited, the range measurement is from a small area centred on the sub-satellite point, and the global topography is seriously under-sampled. For a high inclination orbit at typical altitudes:

$$\text{Mean Equatorial track spacing (km)} \times \text{Repeat period (days)} \approx 1400 \ \text{(km days)}.$$

By careful choice of the orbit parameters, the optimal repeat pattern can be achieved, either as a monotonic offset from day to day covering the gores, or with a more complex subcycle pattern. The orbit selection is a function of the end application of the mission data: Observation of long period Rossby waves, for example, can be carried out with these very long repeat periods. Operational observation of storms (via the wave height product) requires a shorter repeat period and an acceptance of higher levels of aliasing of tidal effects etc.

2.2 SMALL-SATELLITE ALTIMETERS

As discussed above, conventional satellite altimeters have undergone significant reductions in mass and power since the earliest missions. The current state of the art in deployed altimeters is the Poseidon-2 instrument on the Jason spacecraft. This is a dual-band (C and Ku) instrument with a mass of 70 kg and a power consumption of 80 W.

There is little scope for significant reductions in the mass, power or cost by further evolution of the design, as the technology is already quite mature. To achieve a small-satellite solution, we are therefore obliged to consider:

- cutting out ancillary equipments (e.g. the radiometer or the second frequency); and/or
- changing the technology (e.g. Ka-band altimeters).

2.2.1 Ancillary Equipments

Table 2-2 illustrates the main corrections made in an altimeter, including the impact on the errors and the mass and power of the ancillary equipments needed to make those corrections. The values are based on published Envisat figures. It is clear that the corrections are necessary but that the "costs" of the ancillary equipments are significant compared to the radar altimeter itself.

Error Source	*Non-Corrected Effect (cm)*	*Residual after Correction (cm)*	*Correction Method*	*"Cost"*
Instrument Error		~ 2		RA-2 110kg, 160W
Orbit	400–1000	~ 50 ~ 10 ~ 3	Near-real-time orbit navigator DORIS preliminary orbit DORIS precise orbit	DORIS 91kg, 42W ditto + a delay
Sea-State Bias	0–20	~ 2		
Dry Troposphere	~ 230	0.2–2	Model	
Wet Troposphere	0–30	1–2	Microwave radiometer	MWR 25kg, 23W
Ionosphere	~ 20		Dual frequency operation	Say 25% of RA-2, ~30kg, 40W

Table 2-2. Altimeter Absolute Height Errors and Correction Methods

Although it is not in possible to omit the corrections without compromising the altimetry performance, it may be possible to perform them in a different ways – e.g. using GPS rather than DORIS (considered in another work package) or by obtaining the required information from third parties (see §2.2.3).

2.2.2 Alternative Small Altimeter Concepts

CNES/Alcatel have a single- (Ka-) band altimeter in development which has very low mass (20 kg and 50 W). The AltiKa instrument [6] consists of a combined Ka-band (35.5–36 GHz) radar altimeter and microwave dual frequency radiometer 24–37 GHz. Both instruments share the 1.0 m antenna. It is compatible with a microsatellite mission and could economically be launched in constellations. A three-satellite mission is being studied with the three satellites spaced 120° apart in a common plane. The Ka-band operation is almost insensitive to ionospheric error effects, but is significantly affected by rain. The operation is almost beam-limited because of the high frequency, and this permits valid data to be acquired much closer to coastlines that with C-band and Ku-band instruments.

Even simpler altimeters have been studied. For example, the GANDER studies carried out by SOS, SSTL and SEA addressed a mission aimed at monitoring the global wave height field with the intention of providing a commercial ship routing service. A large number of spacecraft (4–8) were to be launched to increase the sampling frequency to a level where, for example, Atlantic storms could be tracked.

The instrument studied was much simplified compared to previous instruments. The main simplification was the deletion of any altitude measurement requirements: the only products were to be wind speed and wave height. This meant that:

- Single-frequency is acceptable, because ionospheric errors may be ignored. Ku-band was selected.
- The phase stability requirements are relaxed compared to precision range measurement instruments. The ultra-stable oscillator requirements are relaxed, and the phase characteristics of the power stages need not be calibrated.

The ROM price estimates for the operational GANDER instrument were at least an order of magnitude below those for earlier scientific altimeters.

For observation of ocean currents most of these simplifications are not applicable, and the requirements must return to a level closer to those for RA-2, Topex/Poseidon and Jason.

2.2.3 Discussion

The entire data collection system must be considered, and the most cost-effective approach will generally be concluded to be one that has a mix of high-cost and low-cost instruments:

- The coverage pattern of the ensemble of satellites must be considered. Missions such as Jason-1 and Jason-2 provide the state-of-the art measurements with orbits selected to minimise tidal effects, and have dual-frequency instruments to calibrate the ionosphere.
- Instruments in less favourable orbits (e.g. the sun synchronous orbit of Envisat) can contribute to the data set after having the tidal aliasing removed by comparison with, say, Jason.
- Water vapour contribution to range bias is determined by means of a model constrained by passive microwave observations from space. This is essentially a meteorological product, and need not be measured on any of the altimetry spacecraft (although it is usually convenient to do so on some).
- Some instruments may be simple single-frequency instruments that rely on track intersections with more sophisticated instruments for calibration.
- Orbit determination may be relatively relaxed on the spacecraft with simple instruments. For example, it may be sufficient to use GPS-based orbit determination on these spacecraft – again cross-calibrated with the more complex and costly spacecraft/instruments.

2.3 NOVEL ALTIMETERS

In the following subsections, we consider concepts to improve the performance and/or coverage for systems that are still basically altimeters.

2.3.1 Doppler Beam Sharpening

Doppler Beam Sharpening, or aperture synthesis, is planned for the SIRAL altimeter on Cryosat. It could also be implemented to advantage in other altimeters, given a suitable transmitter and receiver and some data processing. Pulse-to-pulse Doppler filtering produces a beam (or a fan of beams) with a narrow effective beam-width along-track. Over the ocean, where the surface curvature is very low, this yields an effective along track resolution of ~ 250 m for Cryosat [7].

Doppler beam sharpening requires:

- A coherent radar. In practice, this requirement does not present any significant difficulty if direct digital pulse synthesis and a stable oscillator are employed.
- A minimum PRF in order adequately to sample the Doppler / synthetic aperture. As for an imaging SAR, the sampling requirement is to transmit at least two pulses in each antenna length. For a 1 m diameter antenna at ~ 7000 m/s, the minimum PRF is thus ~ 15 kHz. With such a high PRF, there are then many pulses in-flight simultaneously and there is no time to interleave receive periods between the transmissions. SIRAL therefore operates in a burst mode, transmitting bursts of 64 pulses and then receiving all 64 echoes [8]. These bursts are repeated at ~ 85 Hz, corresponding to ~ 75 m along-track displacement.
- Doppler processing. In the simplest case, the nadir beam at zero Doppler can be formed by simply averaging (complex) samples along track. Non-zero Doppler (squinted) beams can be produced by multiplying the samples by a complex phase-ramp before averaging. If a fan of many squinted beams were required, it would be preferable to do the Doppler filtering by an along-track FFT. In any case, the Doppler processing is not particularly difficult. There is a computational cost but, actually, this is not too demanding:. With N = 64 pulses/burst, $5N\log_2 N$ operations × 128 samples/pulse × 85 bursts/seconds gives a total of ~ 21 Mop/s, i.e. one space-qualified DSP could suffice.

Potential advantages include the following:

- Doppler processing improves the along-track resolution. For our application, this might be useful near coasts (with the right orientation, anyway). However, it is less clear that there is any significant advantage in improved resolution in the open ocean.
- The discrimination in range is also improved, because the echo from the Doppler beam sharpened footprint dies away quicker.
- The performance in the presence of beam mis-pointing in pitch can potentially be improved, as one Doppler beam should still be at nadir.
- Doppler processing improves the signal-to-noise ratio significantly, relative to the SNR in the individual received pulses. This is largely offset by the need to reduce the peak power (or pulse duration) to keep the same average power as for a conventional altimeter with a lower PRF. Overall, there should still be a nett gain of several dB relative to a conventional altimeter with the same average RF power.
- There may be some additional information in separate "looks" squinted forward and backward of nadir. However, the angles will be small (<1°) and it is not clear precisely what useful information could be extracted over the ocean.

SIRAL / Cryosat is intended primarily for measurements of ice, not sea. Since the sea is in general moving, the surface motion might compromise Doppler beam sharpening. The example calculations in Table 2-1 indicate that ocean waves or swell may indeed limit the achievable along-track resolution in relatively rough conditions.

Wavelength (m)	*Amplitude (m)*	*Orbital Velocity (m/s)*	*Equivalent Shift (m)*
100	1	0.8	90
50	1	1.1	130
20	1	1.8	200
10	1	2.5	280
5	0.71	2.5	290
2	0.29	1.6	180
1	0.14	1.1	130

Table 2-3. Equivalent Along-Track Shifts due to Ocean Wave Motion

$$V_{orbital} = a\sqrt{gk} \text{ where } k = 2\pi/\lambda$$

$$\Delta x = h_{satellite} V_{orbital} / V_{satellite}$$

2.3.2 Interferometric Altimeters

The distinction between interferometric altimeters and interferometric SAR is not well defined: In general, the former have narrow beams and view close to nadir using technology derived from altimeter heritage, while the latter do not. The altimeters have very small footprints whereas the radars are designed for large beam size and wide swaths. Here we consider the nadir-looking geometry only; away from nadir, this concept becomes an across-track interferometric radar as considered in §3.

An interferometric altimeter is planned for Cryosat, where it is usefully combined with Doppler beam sharpening (see §2.3.1). Two antennas aligned across-track receive the same echo and measure the phase difference. For echoes arriving from any one direction, the phase difference can be directly translated to the across-track position of the scatterer (given very accurate knowledge of the spacecraft attitude). This is potentially useful for some surfaces with moderate tilts (e.g. ice sheets).

It is important to note that interferometric processing is only able to provide information on the arrival direction of an echo return. It definitely does not resolve overlapping returns (nor does it indicate that overlapping returns are present, unless more than two receiver antennas are used). Doppler beam sharpening can be used to provide good resolution along-track, but across-track resolution is only available if the slant range can be mapped unambiguously to across-track position, i.e. if there is a suitable across-track surface tilt – see Figure 2-2.

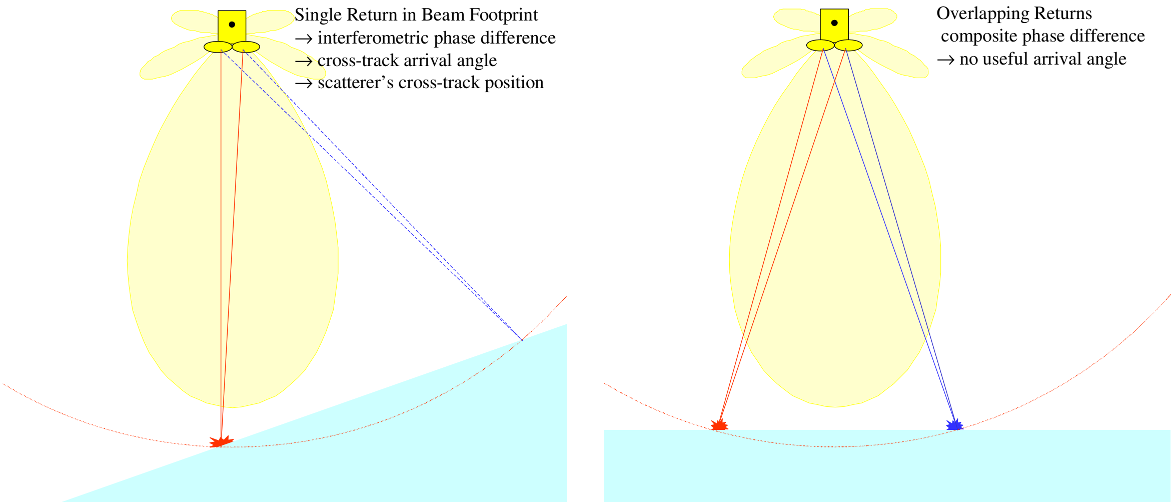

Figure 2-2. Interferometric Returns over Tilted and Horizontal Surfaces
(exaggerated scales)

Where the surface tilt is suitable, which may be the case over some ice-sheets for example, interferometric phase in each range bin can be converted to an across-track arrival angle and then combined with the slant range and Doppler to obtain the scatterer position in three dimensions[1]. In favourable cases, this may give a height profile over a swath width of the order of the altimeter beam width.

For oceans, the tilt within the beam footprint is negligible and, in general, echoes arrive simultaneously from an annulus (or both sides of the track, if Doppler beam sharpening is used). The phase difference is not then meaningful. The phase difference may be meaningful for the first (nadir) return, but the nadir direction is known from the orbit anyway. The nadir phase-difference measurement could perhaps be used to estimate (and maybe then adjust) the satellite attitude, if no better information were available.

In summary, interferometric altimeters of the SIRAL type do not have any real benefit for ocean current monitoring. Since additional hardware (i.e. a second antenna) is required, interferometric altimeters cannot be recommended.

2.3.3 Multistatic Altimeters

Non-nadir-looking range measurements are generally not useful for measuring the ocean height, because the scatterer position (determined only by the beam footprint) can never be known precisely enough to enable the conversion from slant range to height.

One case where off-nadir viewing does appear attractive is that of bistatic (or multistatic) systems. The specular reflection point is defined by the transmitter and receiver positions alone; it does not depend on very precise knowledge of the spacecraft attitude or antenna response. Since the specular reflection corresponds to the first return in the bistatic altimeter, the two-way range can be measured and converted to a surface height at the specular point. The precision can be similar to that for a conventional monostatic altimeter, and most of the issues remain the same.

[1] Accurate knowledge of the attitude (or more specifically, the interferometer baseline orientation) is also needed. Signal-to-noise, bearing accuracies and phase ambiguities are also issues.

Given a constellation of multistatic altimeters, range measurements can be made of several distinct specular reflections:

- to the subsatellite point, as in a conventional altimeter;
- from one satellite to another via the point on the surface midway between the two subsatellite points.

In principle, *N* satellites could provide measurements for *N* nadir returns plus *N(N-1)/2* specular bistatic returns. Consideration of the details, however, indicates that this is not likely to be a realistic assumption – e.g. it would require *N* antennas per satellite[2]. In a chain of satellites, a reasonable limit is a nadir measurement per satellite and a further measurement in each gap (i.e. *2N* for a closed chain and *(2N-1)* for an open chain), made by each satellite interacting only with its nearest neighbours.

Each spacecraft therefore requires:

- A conventional nadir-viewing high performance altimeter
  - dual-band to permit ionospheric corrections to be made
- The conventional supporting sensors:
  - position determination hardware (two or more of DORIS, GPS and laser retroreflector)
  - passive microwave radiometer to assess tropospheric water vapour (although meteorological support may be adequate for this function)
- Two antennas pointed at the specular reflection points on the paths to neighbours. With careful orbit control it may be possible to set the pointing of these antennas before launch, but this is a matter of concern and may drive the solution to one with mechanically steerable antennas.
  - A typical pointing requirement is ~ 0.1°, which corresponds to ~ 40 km positional error. In order to avoid steering mechanisms each spacecraft must fly within a 40 km box relative to the partner spacecraft and relative to the specular reflection point.
  - Since the Earth radius varies by ~30 km with latitude, this is not a straightforward assumption. It is concluded that a prudent design will include an antenna steering mechanism capable of 1°–2° fine adjustment of the pointing and which can be operationally programmed at orbit rate.
- Two parts of a bistatic altimeter electronics unit – one for each of the nearest neighbours:
  - The minimal hardware comprises one receive element and one transmit element, although there are significant reliability attractions in making each of the bistatic parts both transmit and receive.

[2] In principle, one could also consider a single nadir-pointing antenna with either a very broad beam or a phased-array antenna able to form multiple beams electronically.

A broadened beam could cover both the monostatic and bistatic specular points but the SNR would be seriously degraded unless the pulse power was greatly increased to compensate. This might perhaps be an option for 'only slightly bistatic' geometries.

The design and implementation of a phased-array antenna and beam-forming network would clearly be much more difficult than the use of dish reflector antennas. However, overall the use of a single electronically-steerable phased-array might well reduce the satellite mass and recurring costs.

- Synchronisation of the timing of each pair of spacecraft to an accuracy corresponding to ~ 10 mm (the required altitude accuracy). This translates to a synchronisation of ~ 30 ps, which is non-trivial:
  - The optimum solution is beyond the scope of this document, but could include the use of high performance Ultra Stable Oscillators and/or extremely precise GPS time or differential-time extraction.
  - If each bistatic return path is measured in both directions, with the active pair of satellites regularly exchanging roles, then the offset between the spacecraft clocks can be extracted. In essence, this consists merely of averaging the ranges measured in each direction and is therefore straightforward and recommended.

The simplest launch strategy is to deploy the entire constellation into a single plane with a single launch vehicle[3]. The spacecraft can then be drifted apart into their nominal positions.

Height	*Maximum separation allowing intervisibility*	*Min. no. for continuous communications ring*	*Maximum separation for Incidence Angle < 45º*
400km	39.6º	10	7.6º
600km	47.9º	8	10.5º
800km	54.6º	7	13.1º
1000km	60.4º	6	15.5º
1200km	65.4º	6	17.8º

Table 2-4. Limiting Separation Distances

Bistatic altimeter constellations have been proposed in the literature, e.g. 'Bistatic WITTEX' [9]. However, it is far from clear that bistatic operation has any real advantage over monostatic operation. The number of tracks along which measurements are made is equal to the number of altimeters in both cases. In the bistatic case, a reduction in the number of spacecraft buses is offset by the increased size of each bus and the complexity of synchronising the timing and operations over the constellation.

2.4 LASER ALTIMETERS

2.4.1 Principles and Constraints

The basic principle employed in laser altimetry is if course rather trivial – simply the timing of an echo from the surface. Pulsed lasers are invariably used and therefore none of the coherent techniques that can be used with radars are applicable. The hardware requirement is:

- A pulsed laser with a sharp leading edge which can be used to trigger the echo timer
- An optical system used to transmit and receive
- A detector system to stop the echo timer
- An echo timer capable of measuring the transit time to a precision that depends on the mission[4], but is typically a few picoseconds.

[3] Note that this does not prevent the deployment of additional constellations into other planes: it simply assumes that cooperative measurements take place only within a single plane.

A number of constraints apply, including:

- Operation is not possible when the subsatellite point is cloudy (strictly, at the laser wavelength)
- Safety considerations apply. Not only must the laser intensity at the ground be acceptable, but pilots of high flying aircraft must be considered. This constrains the operating wavelength. Wavelengths around 1.5 µm are conventional, although some schemes have been developed which are eye-safe in the visible. All systems need a large telescope for the receiver, but most use a small aperture laser transmitter: by using a common telescope for transmit and receive, the energy is spread over a larger beam and can meet safety rules.

The technology of laser altimeters is in general less developed than radar altimeters, particularly in Europe compared to the US. The small size of such devices, however, makes them particularly suited to planetary missions. For bodies without atmospheres they are of course particularly attractive. Many US missions have carried laser altimeters.

2.4.2 System Geometry

Imperfect overlap between the transmitted beam and received beam is difficult to calibrate and leads to significant measurement uncertainties. A common approach is therefore to ensure that one beam lies entirely within the other. Conventionally the transmit beam is made smaller, as this eliminates any sensitivity to intensity variation within the transmit beam, but the opposite approach is also possible.

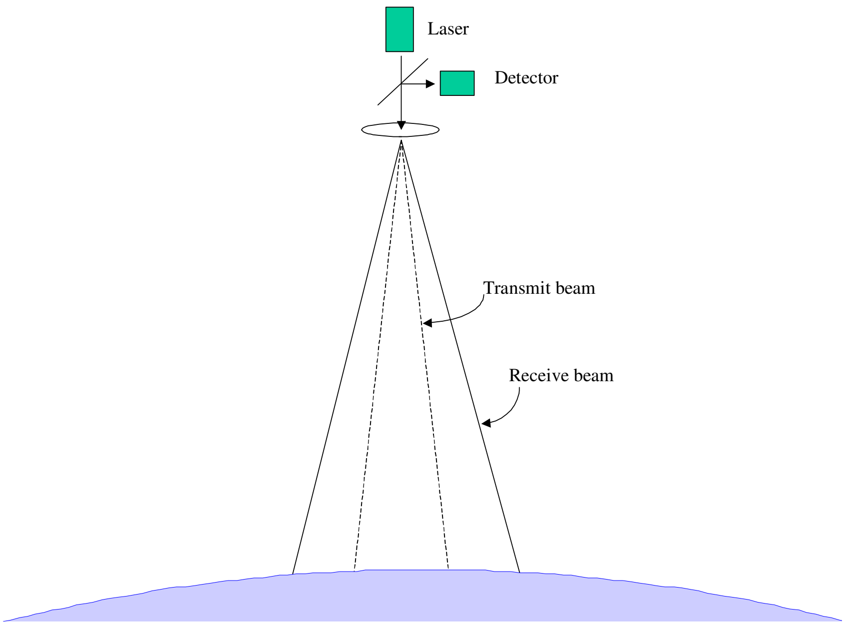

Figure 2-3. Measurement Geometry

[4] 6 ns change in round trip time corresponds to an altitude change of 1 m. An accuracy of 10mm therefore requires (absolute) timing accuracy of 60 ps. If averaging is performed over several pulses, then care must be taken with the repeatability of the pulse shape. Note that any attempt to average to better than the single-shot accuracy places stringent conditions on the bias errors in the system.

With this geometry, all the transmitted photons illuminate the target spot, and the link budget may therefore be computed as below.

$$\text{Received photons} = \text{Transmitted photons} \times \text{R} \times \frac{\text{Collector area}}{\text{Altitude}^2} \times \text{Optical efficiency} \times \text{Quantum Efficiency}$$

where R is a reflectance function which is $(1/\pi)$ for a Lambertian surface and may be much higher (up to 3 orders of magnitude) if the reflection may be considered specular.

A diffraction-limited beam has a spot size at the surface of a few metres[5]. This is inconveniently small and operation away from the diffraction limit is therefore normal. GLAS, for example, is designed for a spot size of ~70 m.

Topographic effects mean that the return pulse is much broader than the transmitted pulse, and discontinuities (e.g. buildings) can mean that the returned pulse may even be bimodal. The echo time measurement is critically dependent on the algorithm used to determine the leading edge of the return pulse. In ocean measurements the slope and roughness can lead to ill-conditioned inversions to range.

This small spot size means that the surface is heavily undersampled in short duration observations. ICESAT makes use of the slow rates of change in the cryosphere and allows a 6 month track repeat pattern, which improves the sampling compared to a single day's observations. If it is known *a priori* that there is no structure at high spatial frequencies then this undersampling is not an important issue. This is not a good assumption in the case of oceans, where wave structures on the scale of the spot size are much larger than the required accuracy and resolution.

2.4.3 Performance

Note that as with radar altimeters the bulk density and the humidity of the atmosphere change the refractive index, and therefore in principle introduce range errors. Unlike radar altimeters, there is no ionospheric component. Providing adequate care is taken with the pressure and humidity corrections, residual errors are expected to be in the range 10-20mm. This is typically smaller than other instrumental error terms.

Typical accuracy for state-of-the-art laser altimeters (e.g. the GLAS instrument on ICESAT) is of the order of 100 mm, which is an order of magnitude worse than required for the measurement of ocean currents. The ICESAT mission can tolerate such errors providing that they are Gaussian with a zero mean, since the mission objective is long term (year-to-year) measurements of changes in ice sheet volume.

Other missions where laser altimeters are particularly well suited are those observing the structure of the vegetation canopy (e.g. to estimate the volume of wood in forests). In these case the small spot size is an attraction, since it permits detailed mapping of the canopy top.

2.4.4 Additional References

See also 'Geoscience Laser Altimeter System (GLAS) Science Requirements' [10], 'An efficient algorithm for the synthesis of laser altimeter waveforms' [11].

[5] $\lambda = 1\ \mu$m, aperture = 1 m, range = 1000 km corresponds to a spot size of 1 m

3 INTERFEROMETRIC RADARS

The majority of this section will consider interferometry with Synthetic Aperture Radar (SAR) as a technique for measuring currents. SAR is a well-proven technology for obtaining high-resolution images of the Earth's surface, which was first demonstrated from space by the SEASAT mission of 1978 [12]. In SAR, a synthetic aperture is formed by coherently integrating the echoes from a large number of successive pulses transmitted along the flight path. This gives a resolution that is equivalent to a real aperture many kilometres long. As a radar instrument, SAR imaging is not prevented by cloud and has therefore been used in a wide variety of terrestrial and marine applications.

The applications of SAR data have been widened through the analysis of phase differences between SAR images of the same scene that are taken from slightly different positions and /or slightly different times. This is the technique of interferometry, which has enabled topographic mapping [13] and measurements of velocity [14]. The concept of measuring ocean currents *directly* is a particularly attractive application of SAR interferometry, as this cannot be done with any other satellite instruments.

In principle, radar interferometry can also be performed using real aperture radar (RAR), although in practice the much coarser achievable resolution may be a problem. The technical feasibility of interferometry with real aperture radars will also be considered in this section, as a RAR instrument could be much smaller and better suited to a dedicated low-cost mission than a SAR – see Annex A and Annex B.

3.1 GENERAL PRINCIPLES

There are two different approaches to SAR interferometry with potential application to the ocean, each measuring quite different information:

- The first is when SAR images are acquired from two antennas separated by some distance perpendicular to the look direction. This is known as across-track interferometry (or XTI). Analysis of the phase difference between the images provides a sensitive measure of the spatial variation of the surface height.
- The second approach uses two antennas separated along the flight path, and is known as along-track interferometry (or ATI). The phase difference between images from the same position at slightly different times is very sensitive to the range displacement of the scatterers during the interval, and thus directly senses (the radial component of) the surface currents.

A more general displacement will produce a combination of XTI and ATI. This is unlikely to be desirable, as it complicates the interpretation of the observations, but may be unavoidable.

An excellent reference for radar interferometry of the ocean is provided by the recent 'KoRIOLiS' report [15] and this has been referred to extensively for this study. Fundamentals of radar interferometry in terms of coherence, phase sensitivity and phase statistics are presented therein and the theory is too involved to be given here. Their findings based on that review of fundamentals, however, can be summarised as follows:

- The time lag between acquired images must be short compared to the decorrelation time. The radar backscatter from the ocean decorrelates very fast and the maximum acceptable time lag is in the order of 50 to 100 milliseconds for L-band (~ 1.25 GHz) and 5 to 10 milliseconds for X-band (~ 10 GHz).

For ATI, the separation of the radars along-track therefore has to be of the order of tens to hundreds of metres for LEO satellite speeds. This implies the need for two satellites in formation (or, conceivably, two radars separated by a long boom on a single satellite) along-track.

For XTI of the ocean, the two images need to be acquired more-or-less simultaneously, requiring two radars in formation (or separated by a long boom, as in the SRTM mission) across-track. This is known as 'one-pass interferometry', in contrast to the 'two-pass' XTI using images from the same satellite on different orbits, which is commonly used for land applications.

- Spatial decorrelation between an XTI image pair can become a problem. Decorrelation occurs when the incidence angles in the two images are significantly different. The effect can be reduced by filtering the signals such that both images use a common horizontal wave-number in the target area.
- On the other hand, the sensitivity of ATI and XTI to variations in the surface current and elevation increases with the respective baselines (antenna separation). An optimum baseline is recommended in terms of a trade-off between the sensitivity and the coherence limit.
- Averaging over a number of pixels can reduce phase noise in ATI images with low coherence. The effectiveness of this noise reduction, however, decreases with decreasing coherence.

Romeiser et al. [15] consider that current measurements by SAR interferometry are most promising for coastal applications. In this case, relatively small amounts of data can be received through existing ground stations, covering major coastal regions in support of a variety of applications. An additional benefit in the coastal zone is the lack of variation of currents with depth, increasing the value of surface measurements for sub-sea applications. For offshore applications, interferometry by real aperture radar may offer a useful technique.

The remainder of this section considers the two techniques of along-track interferometry (ATI) and across-track interferometry (XTI) in separate subsections.

3.2 ALONG-TRACK INTERFEROMETRY

Along-track interferometry (ATI) is the original concept for measuring currents using synthetic aperture radar. It was first proposed by Goldstein and Zebker [13]. Along-track interferometers exploit the difference between two similar radar images of the same area at different times. Then, all other things being equal, the phase difference between the images in any resolution element relates directly to the distance that the scatterers move between images. This can be used in two ways:

- Echoes from stationary scatterers can be cancelled by subtracting the aligned images, leaving only the echoes from moving scatterers, i.e. along-track interferometers can be used as Moving Target Indicator (MTI) radars.
- The phase difference can be used to measure the velocity of the scatterers directly.

The latter is clearly the mode of interest for ocean currents. However, it is conceivable that a single system could be used for both purposes, leading to a dual-use concept that might be more attractive economically.

The theory of using ATI to measure currents was presented by Thompson and Jensen [16]. It is important to note that the ATI technique essentially senses the motion of the dominant radar scatterers, basically the resonant Bragg waves, not actually the underlying ocean currents. Thus, one of the main issues is to account for the other major components of the surface motion, including:

- the phase velocities of the Bragg wave components;
- the orbital velocities of longer waves;
- the hydrodynamic modulation of the surface wave spectrum.

These are all effects at the sub-resolution scale and are dealt with numerically in the ATI imaging models. A state-of-the-art imaging model is the M4S model developed at the University of Hamburg and based on the theory of Romeiser and Thompson [17]. This consists of two modules, a wave-current-wind interaction module [18] and a radar module [17]. The following phenomena are considered when performing ATI simulations with the M4S model, and provide a good summary of the physical issues affecting ATI [15]:

- the contribution to the image of phase differences that corresponds to the surface current field to be measured;
- the effect of the phase velocity of the two Bragg wave components propagating towards and away from the radar, and the different weighting of their contributions to the Doppler spectrum;
- contributions of longer waves, which result from variations of the local normalised radar cross sections and the line-of-sight component of orbital velocity;
- spatial variations of the contributions of Bragg waves and longer waves due to modulation of the wave spectrum by current variations and local winds at sub-resolution scales;
- artefacts of the SAR imaging mechanism, such as the azimuthal displacement of targets that have a velocity component in the line-of-sight direction.

3.2.1 Principle of Operation

Following Kim and Moon [19], the geometry of ATI is shown schematically in Figure 3-1 below. The two antennas are travelling in the x direction (along-track) with a velocity V, and are separated along-track by a distance B. The antennas look sideways, across-track, in the y direction. The time interval for an image of an identical surface area A obtained by the two antennas is given by $\Delta t = B/2V$. The factor of 2 arises from the assumed ATI operating mode whereby the rear antenna transmits the signals and both antennas receive. Thus the first image is obtained under the geometry of Figure 3-1 and the second at Δt later when the rear antenna is horizontally aligned with area A. The phase difference $\Delta\phi$ between the return signals of the two ATI antennas is due to the Doppler shift ω_D and the time interval Δt. This is related to the measured radial component of the surface velocity U_r according to the formula

$$\Delta\phi = \omega_D \Delta t = \frac{kBU_r}{V} = \frac{2\pi BU_r}{\lambda V}$$

where k and λ are the radar wave-number and wavelength respectively. U_r is the radial component of the surface scatterers velocity, given by $U_r = U_\chi \sin\theta$ where U_χ is the range component of the velocity of surface scatterers and θ the radar incidence angle. The radial component of the surface scatterers, U_r , represents the vector sum of the surface currents, phase velocity of Bragg waves and orbital velocity of long waves (swell) [14].

As a phase difference, $\Delta\phi$ can only vary in the range $-\pi<\Delta\phi<\pi$, and this may result in an ambiguous velocity component over the time interval Δt.

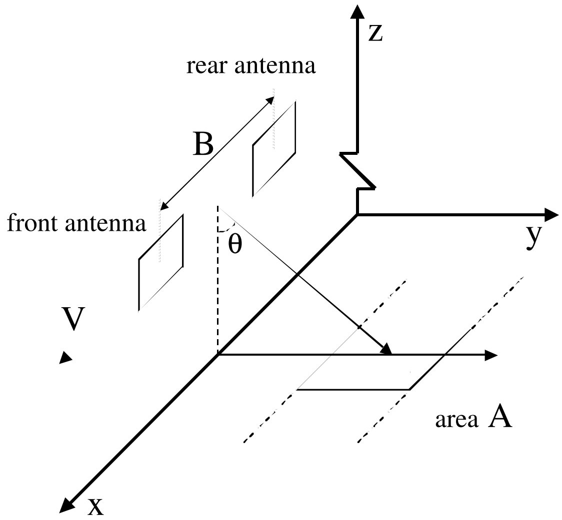

Figure 3-1. Schematic of ATI operation.

3.2.2 Current Retrieval Technique

The conversion of ATI phase images into current measurements is complicated by the effects noted earlier, but despite this the relationship between these images and current velocities (in the line-of-sight) is much more linear than that of other ocean sensors. As a first guess, an ATI phase image can be converted into an approximate current field via a simple proportionality factor and a correction for the mean contribution of wave motions (which is easily computed). Other corrections are smaller and can be made through subsequent iterations.

A schematic for the retrieval of surface currents from ATI phase images, proposed by Romeiser et al. [15], is given in Figure 3-2. A first-guess current field is obtained through direct inversion of the observed phase image. This becomes the initial state for the ATI imaging model, which then performs iterations in conjunction with the data analysis and optimisation tool to produce the final current field.

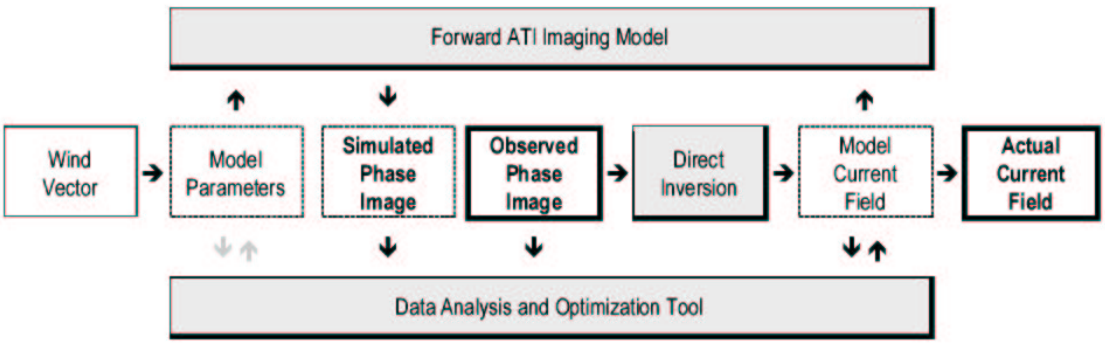

Figure 3-2. Schematic for the retrieval of surface currents by along-track interferometry (from Romeiser et al. [15]).

3.2.3 Influence of Radar Parameters

The dependences of ATI signatures of current fields on different radar parameters are presented in a comprehensive study by Romeiser and Thompson [17]. In summary, the principal effects relate to radar frequency, polarisation, incidence angle, antenna separation, and the ratio of target range to platform velocity (*R*/*V* ratio).

a) Radar frequency

Thompson and Jensen [16] reported that high microwave frequencies are preferable for using ATI to measure currents due to the reduced hydrodynamic modulation of the Bragg wave components leading to more linear current imaging. In a study of L- and X-band ATI, however, Romeiser and Thompson [17] did not find a definite advantage with using higher frequencies. They suggest that frequency is not a critical parameter for ATI measurements of currents but note that frequency will influence system specification.

Since radar instruments are generally smaller at higher frequency, X-band would seem to be a good choice.

b) Polarisation

Polarisation of the ATI system is not a critical parameter from an inversion point of view, but the higher normalised radar cross section of the ocean for vertical (VV) polarisation results in a better signal to noise ratio. VV is therefore the recommended polarisation for ocean ATI, with cross polarisation being the least favourable option.

c) Incidence angle

For clear signatures of surface current patterns, the incidence angle should be as high as possible. At low incidence angles, the contribution of vertical components of orbital wave motions is a large component of the ATI signature, and the variation of this with the hydrodynamic wave modulation results in strong non-linearities in the imaging mechanism. Ideal incidence angles for ATI current measurements are reported to be between about 35º and 45º [17].

A low-to-moderate resolution SAR operating in scanSAR mode can actually cover a wide range of incidence angles, e.g. 20–50° (see Annex B). In order to improve the spatial/temporal coverage, it is clearly desirable to use as wide a swath as possible. However, if the data at 20° incidence is not actually useful, it is not worth collecting it. It could be possible to move the swath to rather higher incidences, but not very desirable as the instrument design rapidly becomes more difficult beyond about 50°.

d) Antenna separation

Because the time between acquisitions must be short compared to the decorrelation time of the signal, maximum acceptable time lags are reported to be 50 to 100 milliseconds for L-band (1 GHz) and 5 to 10 milliseconds for X-band (10 GHz) [15].

Aliasing of the phase difference is a second potential constraint on the maximum acceptable time lag. The phase will be ambiguous if the two-way slant range to the scatterer changes by more than half a wavelength. The maximum radial velocity is therefore given by $2|\Delta U_{max}|\Delta t = \lambda/2$. For the purposes of illustration, if the maximum unambiguous radial velocity were taken as ±1 m/s, the maximum time lags for L-band ($\lambda \approx 0.3$ m) and X-band ($\lambda \approx 0.03$ m) would be 75 ms and 7.5 ms respectively. In practice, 1 m/s might not be big enough, in which case shorter lags would be needed.

For a satellite travelling at 7 km/s = 7 m/ms, a 50 ms delay (for L-Band) corresponds to a two-way phase centre separations of 350 m, and 5 ms delay (for X-band) corresponds to 35 m. Assuming transmission on one antenna and reception on both, one two-way phase centre is at the centre of the transmit antenna and the other is midway between the two antennas. Then the maximum antenna separations are 700 m for L-band and 70 m for X-band.

There is no particular minimum separation, apart perhaps to avoid physical overlap of the two antennas. However, all other things being equal, the velocity measurement accuracy increases with increasing separation.

Thus, the optimum separation is near to the maximum separation permitted by decorrelation and phase-aliasing, i.e. maybe 500 m for L-band or 50 m for X-band.

e) *R*/*V* ratio

The ratio of the target range (*R*) to platform velocity (*V*) determines the non-linearity of the SAR imaging mechanism. With satellites, *V* is fixed by the orbit parameters, while *R* will also depend on incidence angle. For a typical altitude of 800 km, *V* is 7 km/s and for an incidence angle of 45°, *R*/*V* is about 160 s. At this value, the non-linearities are fairly pronounced, but they are well understood and can be accounted for in the current retrieval algorithms.

3.2.4 Influence of Environmental Parameters

The effects of environmental parameters on ATI signatures of currents are also described by Romeiser and Thompson [17]. The sensitivity of the technique to the wind and wave regime is summarised here.

a) Wind speed

Model results of Romeiser and Thompson [17] did not show a significant dependency of ATI signatures on wind speed, but these results are averaged over many simulations. In theory, high wind speeds give a large radar cross section and reduced hydrodynamic modulation of Bragg waves, both desirable for ATI imaging, but may have unfavourable effects relating to wave intensities and corresponding non-linearities in the imaging mechanism. The wind speed influences the peak wavelength (in the order of wind speed squared) and it will be difficult to retrieve currents on spatial scales less than this [15].

The lowest useful wind speed for ATI imaging is determined by the signal-to-noise ratio of the radar image, since the backscatter cross-section of the ocean depends strongly on the surface roughness and wind speed[6].

b) Wind direction

Wind direction affects the intensity ratio of the Bragg wave components, which determines the offset of the ATI currents compared to actual currents. Wind direction also affects the hydrodynamic modulation of longer waves and therefore the non-linearity of the imaging mechanism. These effects are minimised in the case of wind direction parallel to current direction, but an exact knowledge of the wind direction is generally required in order to correct the data for these effects.

[6] The signal-to-noise ratio also depends on the operating incidence and the radar design, see Annex B.

c) Wave spectrum

In the numerical simulations performed during current retrieval, the wave spectrum is assumed to be determined by the wind regime and parameterised accordingly. This may not be appropriate under certain conditions, such as when the wind changes shortly before acquisition, when swell waves originate from outside the target area, in the presence of atmospheric or ocean turbulence, or in coastal areas where wind and wave conditions are localised. It is therefore desirable to have as much information as possible about the wave regime (this is partly measured by the ATI technique itself, see Romeiser et al. [15]).

3.2.5 Accuracy and Spatial Resolution

The ATI accuracy and spatial resolution are limited by incoherence (including ocean decorrelation and additive noise) in the data and by signatures from moving components, such as the long waves.

a) Current Accuracy

The current measurement accuracy is determined by the error in the interferogram phase measurement, the ATI time-lag and the wavelength. The phase error accuracy as a function of coherence is summarised in Figure 5-4 of [15]. This shows that, unless the coherence is very high, it is essential to average multiple independent radar looks in order to achieve reasonable phase accuracies.

As an example, consider an X-band ATI system with 56 m antenna spacing, transmitting on one antenna and receiving on both so the effective time-lag is 28 m ÷ 7 m/ms = 4 ms. The maximum observable velocity in such a system is given (see above) by $|\Delta U_{max}| = \lambda/4\Delta t \approx 1.9$ m/s radially (and hence ~2.8 m/s along the surface for 45° incidence).

Assuming the radar design ensures a high signal-to-noise ratio (for the wind speed in question), the coherence is determined mainly by decorrelation. For a typical X-band decorrelation time of 15 ms, equation 5-17 of [15] suggests the coherence is about $1\times\exp\{-4/15\} \sim 0.75$.

With 20 looks, their Figure 5-4 indicates that the RMS phase error is about 9° ($\pi/20$ radians). Then using $\Delta\phi = 2\pi(2U_r\Delta t)/\lambda$ gives the RMS radial current error as $(1/20)\lambda/4\Delta t$ or ~ 0.1 m/s.

b) Current Bias

Assuming for now (see §3.2.6 b below!) that the relative satellite across-track positions are very accurately known, the wind velocity is known and the ATI retrieval model is optimised, the inversion algorithm should be able to remove the unwanted effects. It could then be possible to achieve a bias (difference between mean current from ATI and actual mean current) of 0.1 m/s for absolute currents.

Relative currents within a target area will be better still [15]. It is not necessary to know the relative satellite across-track positions very precisely in order to obtain the relative currents.

c) Spatial Resolution

The spatial resolution of the measured currents depends on the radar spatial resolution and also on the number of independent looks needed to extract accurate ATI phases.

Existing strip-map SARs (XSAR, ERS, ASAR) typically provide 4 looks at ~ 25 m resolution. If many looks are needed, the resolution can be degraded in both dimensions, e.g. 100 m resolution and ~ 64 looks. For this class of strip-map SAR, the swaths are typically 50–100 km wide (generally at the lower end for the incidence angles near 45° best suited for ATI).

Future SARs focusing on land and security applications (e.g. the proposed TerraSAR-X) may provide much finer resolution (of the order 3 m single-look, or 25 m for 64 looks) but over much narrower swaths (~ 20 km). This domain is probably less appropriate for the ocean current application.

ScanSAR systems provide wider swaths at lower resolution. An example scanSAR concept, with ocean applications in mind, is described in Annex B. This could provide 4 looks at 100 m resolution, or therefore 64 looks at 400 m resolution by pooling image pixels, over a swath up to 500 km wide. Changes to the SAR design would allow other combinations, see §B.5.

3.2.6 Practical Issues

a) Single satellite vs. two-satellite formation

As noted above, the spacing of L-band ATI antennas would be so large that the only realistic solution is an along-track formation of two satellites.

In some respects (especially instrument size), an X-band system is preferable, and then the ideal separation (~ 50 m) is more problematic. Two alternative options are a pair of satellites in close formation or two radars on a single satellite separated by a very long boom. The boom approach is feasible in principle, and a 60 m mast was recently used for the Shuttle Radar Topography Mission [20]. However, much work would be needed to develop a boom suitable for a small mission. For example, the SRTM mast and its associated deployment canister weighed about 1 tonne in total [21] and is clearly not directly applicable to a small mission. Also, a long boom would present severe AOCS problems on anything smaller than the Space Shuttle. Hence, the formation is probably still the only realistic choice. Although free-flyers at 50 m separation are rather close for comfort, the safety aspects should not be prohibitive[7].

b) Across-track alignment

Spatial decorrelation is not a problem for along-track interferometry, as the across-track offset between the images is nominally zero. However, the relative across-track position of the two receive arrays is very critical, as any small displacement introduces a phase shift and hence a bias in the measured currents[8]. The relative across-track positions need to be known to an accuracy compatible with the phase shift expected for the minimum velocity of interest, i.e. very much better than a wavelength.

[7] In any case, the ATI operations require much tighter positional control than collision avoidance. However, the safety aspects would be a big concern if one wanted to fly a second receiver very close to a third-party transmitter – both because of the natural concern of the third-party and because of technical aspects, (different drag characteristics, EMC, etc.)

[8] Near coasts, any current bias can easily be removed by subtracting the apparent phase shifts of the land. This is the case for many published ATI papers, but is not an option over the open oceans.

The absolute satellite positions and attitudes (even after restitution) cannot possibly be expected to achieve the required millimetre level of accuracy. Instead, some specific instrumentation will be needed to measure the relative positions of the two antennas, whether on the same satellite or separate ones. This might include differential GPS, a precise ranging system (to measure the inter-antenna baseline) and/or accurate star-trackers (to measure the baseline orientation). SRTM's Attitude and Orbit Determination Avionics subsystem comprised: two GPS receivers; a star-tracker; an inertial reference unit; an optical camera tracking three LEDs on the outboard antenna; a terrestrial COTS Electronic Distance Meter (a Leica electro-optical device); and two analysis and control computers.

The control of the position and attitude needs to be quite good (say of the order of a metre and a small fraction of the beam-width) but is nowhere near as critical as the *knowledge* of the phase-centre positions.

c) Along-track alignment

Along-track alignment is less of an issue, and the along-track spacing might only need to be controlled to say ±10% of nominal. The knowledge of the along-track separation must be rather better, say to a small fraction of the antenna length, in order to ensure proper alignment of the images and avoid degrading the interferogram. In any case, compared to across-track, the along-track separation is easy to measure with a ranging device.

d) Orbit and formation geometry

The choice of orbit would be determined by consideration of the spacecraft design and the achievable coverage. A LEO orbit is preferred for SAR, but the precise orbit height is a trade-off of various factors including link budgets, swath width and repeat cycle. From a spacecraft viewpoint, a dawn-dusk sun-synchronous orbit is attractive because it would ease the power system design. However, a lower-inclination, non-sun-synchronous orbit would give slightly better coverage of the main regions of interest. An example of some possible coverage statistics is included in §B.4.

Assuming a two-satellite solution, the formation geometry for ATI is clear – the two satellites are in close line astern along the same ground track. Provided the individual satellites are small enough, they could clearly share a launcher.

e) Coordination of satellites

Coordination of the satellites is necessary at a number of levels:

The overall operations schedule (e.g. warm-up and switch-on approaching oceans) needs to be coordinated, though this may simply be by command from the ground.

The detailed radar operations (setting parameters, beam steers for different subswaths, etc.) must be coordinated continually. If the two satellites were identical, it would be desirable to share the transmit power load between them, and this aspect would also need to be coordinated[9]. A low data-rate link between the two satellites would suffice for this. Such a link should be very easy given the small separation (a COTS wireless LAN might provide a cost-effective solution!).

[9] In a scanSAR system, it would be straightforward to switch the transmissions between satellites at the same time as changing subswaths. However, for a strip-map SAR, there is no really convenient time to switch transmissions in mid-stream. It would greatly complicate (but not necessary prevent) the processing if the transmissions were switched on a pulse-to-pulse basis.

The most critical timing requirements relate to the radar data itself. The pulse transmit and receive timing must be accurate to much better than the achievable time resolution in slant-range, and the local oscillator frequencies need to be matched or monitored. This might require specific instrumentation, though it need not be particularly sophisticated and the close proximity is helpful.

f) Data handling

The volume of data from a SAR is always significant, see §B.4, and an ATI system requires at least two SAR receivers. The simplest approach would be to store all the receive data, down-link it and process it on the ground. However, the amount of on-board storage needed and the down-linking requirements would be very onerous.

The data volume would be very substantially reduced if the data were processed on board. The achievable data reduction could be of the order of the number of radar looks combined to extract each ATI phase / current measurement, maybe a factor of 50 or more. However, the processing requirements are far from trivial, and include the SAR raw-to-image processing for each receiver, precise co-registration, and phase difference processing. The last of these is relatively easy. Given sufficiently precise datation, co-registration might be possible "open loop", in which case it is straightforward. Otherwise, computationally intensive iterative correlation techniques over the whole swath would have to be used (there generally being no suitable tie-points in mid-ocean). SAR processing is also extremely computationally intensive and is not really feasible in near-real-time with existing space-qualified/qualifiable technology [22].

3.3 ACROSS-TRACK INTERFEROMETRY

Across-Track Interferometry (XTI) employs two (or more) receive apertures separated in the cross-range direction. The phase difference between signals received on the two apertures gives information about the scatterer position. This can be used…

- to give a fine bearing estimate for a point signal (the so called phase-monopulse technique, often used with real aperture radars) (c.f. Cryosat, §2.3.2);
- between (synthetic aperture radar) images to give interference fringes, which in turn can be related back to terrain heights, sometimes referred to as InSAR.

Phase-monopulse cannot provide adequate height accuracy on a single echo, so our main interest here is in the InSAR XTI approach. SAR XTI from space is well established for land applications, following extensive work at DLR and elsewhere. In outline, XTI consists of the following steps:

1. Generate the two SAR images, using consistent processing parameters to maximise the coherence between the images.
2. Co-register the images very precisely, and resample onto a common grid. (For a dedicated ATI mission, it might be possible to ensure adequate co-registration by instrumenting and coordinating the radar operations.)
3. Determine the phase difference between co-registered resolution cells.
4. Remove the phase difference trend versus slant range expected for a nominal surface (e.g. a reference ellipsoid).
5. Smooth the phase differences (using a sliding boxcar averager or similar).

6. Unwrap the phase differences[10].
7. Interpret the unwrapped phases as height deviations from the nominal surface.

Although there are a number of difficulties in practice, this is now done quite routinely for SAR images over land. Over suitable terrain, XTI can yield height precisions of better than 1 m, over small areas at least. Over longer scales, errors due to incorrect phase unwrapping tend to accumulate and the accuracy degrades (unless known altitude tie-points are included).

3.3.1 Issues for XTI over the Ocean

XTI over the ocean should be feasible in principle, but there are some significant differences to the established land case:

a) Temporal Decorrelation

As already noted in §3.1, because of the rapid decorrelation of the sea surface, the two images must be captured near-simultaneously. The two-pass interferometry technique most commonly used on land is therefore not applicable. As for ATI, we need a second antenna, which may be a receive-only one, but unlike ATI it must be offset across-track / vertically.

b) Spatial scales

The underlying slope of the ocean is very low. Problems such as layover and phase discontinuities[11] are then much less of an issue, and the spatial resolution can be much coarser. On the other hand, it is necessary to ensure extremely robust phase unwrapping and conversion to height over very long distances, in order to observe the very small slopes of interest[12].

c) Baseline and baseline decorrelation

The achievable height accuracy is proportional to the inter-antenna baseline. Given the very small height changes of interest, the baseline should be large. That is, the second antenna should be on a second satellite or on an extremely long boom like SRTM [20].

Spatial decorrelation may impose an upper limit on the baseline. However, decorrelation can be avoided by using slightly different frequency bands for the two incidence angles (such that the wave-numbers projected onto the ground are the same). If the bandwidth is fixed, the range resolution will be degraded (until the baseline increases to the critical value, at which point no image is possible at all). Alternatively, the transmitted pulse bandwidth may be increased to compensate for the increasing baseline whilst maintaining the resolution. There are then costs in power (or SNR) and data-rate, and the antenna design may become more complex too. Nevertheless, this may be the only way to provide an adequate baseline to achieve the required height accuracy.

[10] I.e. attempt to remove the $0/2\pi$ phase discontinuities in the data. This is far from trivial in a noisy 2-D image that may be subject to shadowing and layover.

[11] Layover occurs when echoes from two or more separate areas, at different heights and plan positions, happen to fall in the same image pixel. Phase discontinuities occur when the terrain height changes sharply between resolution cells, and are problematic if they exceed $\pm\pi$.

[12] Throughout this subsection, it is assumed that we are attempting to measure the mesoscale variations in the mean ocean height, and thence derive the currents. A high-resolution XTI SAR system could resolve and derive height profiles for the longer wind waves and swell. The latter case is not considered here, as it represents a completely different domain in terms of length-scales and slopes.

d) Corruption by ATI effects

The phase effects expected from XTI due to mean ocean surface height variations are very low. In contrast, ATI would be very sensitive to any radial motion if there were any significant lag between the two images, and any spatial variations in the currents or hydrodynamic effects might totally mask the XTI signature. Thus, it is important to avoid any lag between the two images. This impacts on the XTI SAR processing requirements and may result in a reduction in the coherence.

e) Formation issues

For XTI, the antennas need to be aligned across-track. More precisely, the inter-antenna baseline must have a suitable component normal to the radar look direction, but with little or no along-track offset. So, in principle, a vertical antenna baseline would be as good as a horizontal across-track baseline for an XTI measurement.

A suitable geometry for XTI is harder to achieve than the along-track formation needed for ATI. The problem with an across-track or vertical formation is that the satellites do not naturally remain in the same relative positions around the orbit[13]. Instead, the satellites in an inertial formation appear to execute an ellipse about a common centre once during each orbit round the Earth. Thus, the baseline between satellites is always changing, and at some points round the orbit there is no baseline component in the required direction. Also, it is a feature of inertial formations that the amplitudes of the along-track and vertical motions are constrained to the ratio of 2:1. Significant vertical baselines are therefore not desirable because, at other times, they will transform to larger along-track baselines causing ATI / azimuth decorrelation effects.

A purely-across-track formation does not suffer in this way and is preferred. The formation then executes a linear oscillation across-track (referred to as an ‘Interferometric Pendulum’ in [15]). A constant baseline cannot be maintained and the best that can be done with two satellites is to choose a formation that gives an ideal baseline at two points round the orbit, and accept the non-ideal baselines elsewhere. More satellites would provide more baseline options and a more even distribution of near-ideal baselines around the orbit.

The perfect interferometric pendulum with no along-track separation has one serious flaw, which is that the satellites would crash at the point where they cross over. Thus, some ellipticity must be introduced into the formation motion; both vertical and along-track motions must occur, because the two components are linked.

f) Position keeping and knowledge

Generally, for XTI, the position of the two antennas is nowhere near as critical as for ATI. For land mapping, the baseline length and orientation in space generally only needs to be known only to the order of 1% and 1°.

However, this may not be the case for larger-scale XTI observations of the ocean, as the slopes to be measured are extremely low. Intuitively, in the absence of external corroboration such as tie-points, it seems clear that the baseline orientation must be known to an accuracy better than the smallest surface slope of interest.

[13] That is, unless they continually perform quite large ΔV manoeuvres. But, since this would be prohibitive in terms of fuel load or mission life, a natural inertial formation is more-or-less mandated.

g) Other issues

Some of the other issues discussed for ATI in §3.2.6, such as data handling and satellite coordination, are also applicable to XTI.

3.3.2 Accuracy and Spatial Resolution

The interferometric phase accuracy is limited by incoherence, including the effects of decorrelation and noise. The phase accuracy as a function of coherence is summarised in Figure 5-4 of [15], and is applicable for both ATI and XTI.

Similar to §3.2.5, phase accuracies of the order of 9° ($\pi/20$ radians) might be expected. As for the ATI case, this assumes ~ 50 SAR looks. This might correspond to a spatial resolution of ~ 100 m for a strip-map SAR like X-SAR or ~ 400 m for a wide-swath scanSAR system (as in Annex B).

The interferometric phase maps to a vertical displacement via a consideration of the geometry. It can readily be shown that $d\phi/dz = (4\pi B_\perp \sin\theta/\lambda R)$, where $B_\perp$ is the baseline orthogonal to the line of sight and z is the surface height displacement. Consider an X-band XTI system with a 200 m antenna spacing, transmitting on one antenna and receiving on both so the effective baseline is 100 m. At say R=1000 km and θ=45°, the RMS height error of a single measurement is then $(\pi/20)$ / $(4\pi B_\perp \sin\theta/\lambda R)$ ~ 5 m.

If the surface slope is low and the phase unwrapping is totally robust, the surface height accuracy can be improved by further averaging. Averaging over blocks of $n \times n$ height estimates should improve the RMS error by a factor of n. Hence, as an order-of-magnitude indication at least, we can expect the following XTI performance:

- Strip-map SAR: 1.0 m RMS height at 500 m resolution;
  0.1 m RMS height at 5 km resolution over a 50–100 km swath
- ScanSAR: 1.0 m RMS height at 2 km resolution;
  0.4 m RMS height at 5 km resolution over a 500 km swath

3.4 REAL APERTURE RADAR CASE

In principle, radar interferometry could be performed using Real Aperture Radar (RAR) instead of Synthetic Aperture Radar (SAR). A real aperture radar is much simpler to implement than a SAR, but the spatial resolution would be very much coarser than that of a SAR – compare Annex A and Annex B. Nevertheless, a RAR might still be useful for open oceans at least, given the spatial scales and very low ocean slopes envisaged.

An example real-aperture radar is described in Annex A, together with a discussion of the available high-level design trade-offs. Some of the key points are as follows:

- A minimum PRF (to sample the synthetic aperture) is not required, so the PRF can be reduced to eliminate range ambiguities. Then the antenna height can be small.
- With no range ambiguities to worry about, the elevation beam-width and swath-width can be almost arbitrarily large. Electronic beam steering would therefore not be required and a very simple passive antenna can be used.

- There is no minimum antenna length to avoid azimuth ambiguities. The antenna length is just a trade-off between instrument complexity and resolution (= beam footprint size) in azimuth. The azimuth resolution will always be coarse, of the order of 10 km or more. The frequency needs to be high, and might usefully be increased beyond X-band, to improve the azimuth resolution. Even so, the antenna must still be quite long[14].
- Much less power is required for a RAR than a SAR (as a direct consequence of the larger signal returned from the larger resolution cell). A typical link budget is included in Annex A.
- The processing is nowhere near as complex as for a SAR, and could more easily be implemented on-board in real-time. Pulse compression will be required, in order to keep the peak power within reasonable limits, so some processing will remain.

The interferometric processing for a RAR is essentially the same as for a SAR, for both XTI and ATI. The same issues apply, in particular temporal decorrelation / along-track separation; spatial decorrelation / extra bandwidth to avoid spatial decorrelation.

Of course, the biggest issue is the much-degraded resolution in the RAR case. This is exacerbated by the requirement for a large number of independent radar looks in order to achieve adequate interferometric phase accuracy. For SAR, this meant that the ATI/XTI product resolutions (for useful accuracy) would be much coarser than the basic radar resolutions, see §3.2.5 and §3.3.2.

For the RAR system considered in Annex A, the single-look radar resolution is of the order of 20 km in azimuth and 4 km in ground range. It is unlikely to be acceptable to degrade the product resolution in azimuth beyond 20 km. If the range resolution were degraded to 20 km as well, this would give 5 range looks. There are also some independent looks along-track, as the PRF assumed is about 15 times the minimum needed to provide continuous coverage along-track. If the two satellites transmitted alternately and received both sets of pulses, this would provide another factor of 2. Thus, the example RAR system in Annex A could provide the required high number of looks at 20 × 20 km resolution.

For **ATI**, there seems to be no reason why a pair of these radars could not produce current measurements at this resolution[15]. If the inter-antenna spacing is taken as 56 m, the same as in §3.2.5, and with the same assumptions, then the predicted RAR ATI performance can be summarised as:

- 0.1 m/s RMS current accuracy, at 20 km resolution, over a 500 km swath[16].

For **XTI**, the situation is different because of baseline decorrelation, see §3.3.1c. With a 100 m baseline, as assumed in §3.3.2, the XTI frequency shift at X-band at (say) 45° incidence is given by $\Delta f = f_0 B_\perp / R\tan\theta$ = 1 MHz (c.f. equation 5-15 of [15]). This must be contrasted with the pulse bandwidth of 0.05 MHz assumed for the RAR system in Annex A. With this combination of pulse bandwidth and baseline, the coherence would be zero and no meaningful phase differences could be obtained.

[14] E.g. a 3 m aperture at Ku-band (~ 13.5 GHz) gives ~7 km azimuth footprint at 1000 km slant range.

[15] The details of the inversion of ATI phases to the currents may differ from the finer resolution SAR case. Arguably, removal of the biases such as the wave effects might actually be easier at the coarser resolution, because of the greater averaging.

[16] Unlike a SAR, the swath width of a RAR can be increased cheaply. The cost is basically just an increase in the power (or else a decrease in the SNR) and an increase in the date-rate, proportional to the swath width.

It would be unacceptable to reduce the baseline by a large factor (e.g. 40 to provide 50% coherence) because this would degrade the height accuracy by the same factor. Increasing the radar bandwidth to > 1 MHz would increase the power requirement by a similarly large factor. At a single incidence angle, the simplest expedient would be to keep the same bandwidth but transmit pulses at two frequencies separated by the right amount. Unfortunately, different frequency shifts are required for different across-track separations; for the 36–58° incidence angle range considered in Annex A, the shifts range from about 0.6–1.4 MHz. Then the minimum frequency coverage would be two bands 0.4 MHz wide offset by 1 MHz between satellites. The bands would need to be adjusted round the orbit as the baseline varies. The implementation should be straightforward, as the total bandwidth is still not high, but the power and data-rate would have to increase by an order of magnitude.

Another problem with RAR XTI could be the achievable accuracy / resolution. Following the same reasoning as in §3.3.2, and assuming (as discussed above) the RAR provides enough radar looks at 20×20 km resolution to give an RMS phase error of the order of 10°, the RAR performance is

- 5 m RMS height at 20 km resolution; or
  1 m RMS height at 100 km resolution over a 500 km swath

This does not look very useful in practice.

The RAR XTI performance might be improved by increasing the baseline and/or using more looks. In either case, the bandwidth would have to be increased further (to compensate the increased baseline decorrelation and/or to provide extra range looks). The power would then have to be increased to maintain the SNR, and the data-rate would increase too.

3.5 OTHER INFORMATION PROVIDED BY THE SENSORS

The focus of this study is the measurement of ocean currents. However, space-based radars can provide much other valuable information that, taken together, might make a mission viable.

- SAR observations of the ocean and coastal zones provide information including backscatter cross-sections (related to surface roughness) and (depending on the resolution) wave spectra.
- Satellite SAR imagery of land has a wide range of applications, including forestry, crop monitoring / ‘precision agriculture’, planning, disaster support and military surveillance. Commercial (or at least semi-commercial) systems, such as TerraSAR, are being considered to address these markets. The SAR image parameters (in terms of resolution, polarisation, etc.) preferred for these applications are different from our case, and some compromises would be required to combine the land and ocean currents roles. However, the flexibility of SAR systems to provide high-resolution images (in strip-map mode) and wide-swath images (in scanSAR mode) is helpful. For this reason, the proposed X-band component of TerraSAR (which is largely driven by a desire to provide very high resolution imagery) is actually not too dissimilar to the instrument described in Annex B (designed to provide a wide swath at low resolution).

- Across-track SAR interferometry is already widely used on land, and is an important potential commercial market. Applications include terrain mapping and (by differential interferometry) monitoring of subsidence and volcanic/tectonic displacements over time. Applications using XTI of deployed transponders are also being investigated currently. Traditionally, land applications have (of necessity) used images from separate orbits for XTI, i.e. two-pass interferometry. The one-pass XTI needed for ocean applications has advantages for land; in particular, it should allow XTI and differential XTI of vegetation (which decorrelates between separate passes), opening new potential markets in agriculture and forestry.
- Along-track SAR interferometry is used (in MTI guise) on land for detecting moving targets, principally in a military context. The issue of preferred resolution again arises, but the comments above relating to SAR imagery again apply.
- Real Aperture Radar of the ocean is employed in wind scatterometers, e.g. SCAT on ERS and ASCAT being implemented for Metop. These use ocean backscatter measurements from several look directions to estimate the local wind field. Small-satellite formations can be envisaged which would support both ATI and wind scatterometry. Some possibilities are illustrated in Figure 3-6 and Figure 3-7 below. Note that the extra beams needed for scatterometry would also allow additional squinted ATI modes that can usefully measure two components of the surface current.

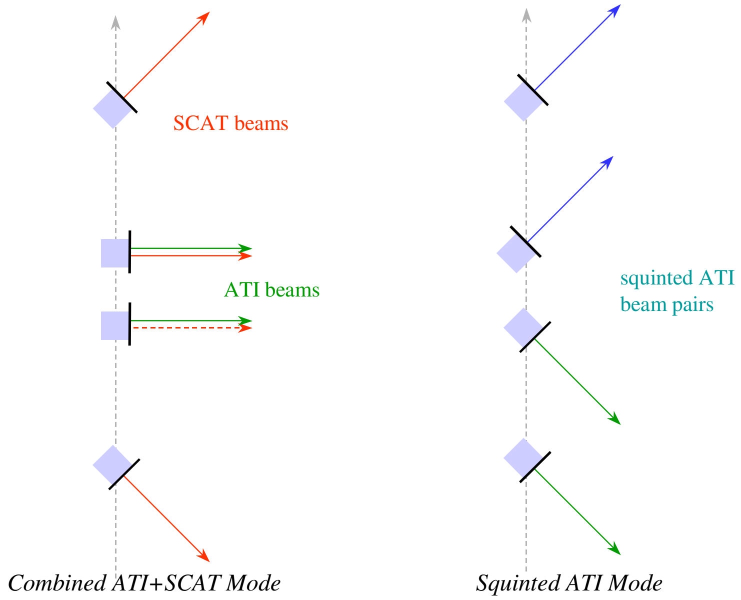

Figure 3-6. Formation Combining ATI and Scatterometer Modes

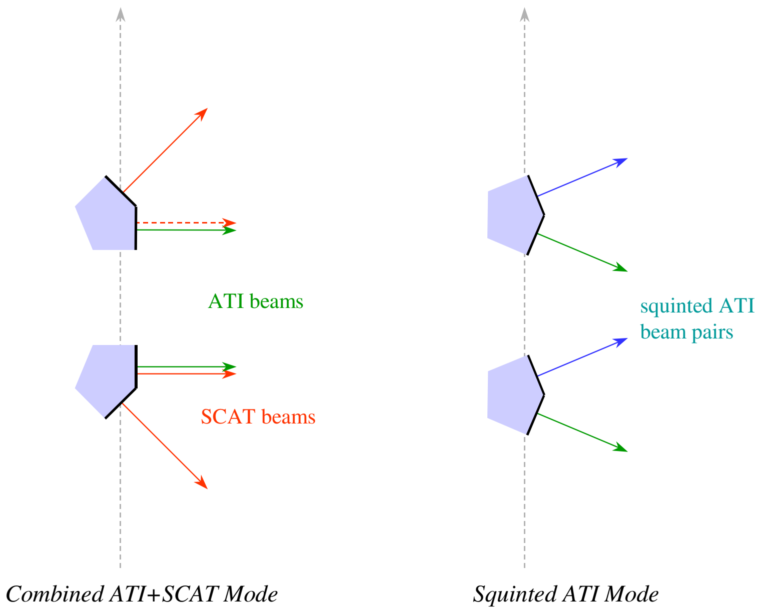

Figure 3-7. Formation with Two Beams per Satellite

- RARs at high frequency might be used as rain radars. Indeed, if the frequency is increased beyond Ku-band (e.g. in order to improve the azimuth resolution for a given antenna length) the instrument will operate as a rain radar whether it is intended or not. At the high incidence angles in question, any returns from rain will overlay the sea returns from shorter plan ranges. The ability to distinguish between sea surface and rain echoes may then be essential, in order to provide quality control for the current measurements. This might be possible on the basis of the observed coherence, if the rain decorrelation time is shorter. Alternatively, extra information from multiple polarisations or frequencies could be provided and exploited. This would have obvious costs, e.g. a factor of two in power, data-rate and antenna height. However, these costs might be more than offset by the benefits of obtaining wide-area rain fields over the open ocean.

Note that these spin-offs do not necessarily come at zero cost. Often, some compromises in the system parameters are required, and higher resolution land applications may come to drive aspects of the design such as transmit powers. It may also be necessary to deliver additional high data-rate information, impacting on the on-board data storage and down-linking aspects.

Some of these additional applications above may actually represent more viable markets than ocean currents, in which case the ocean currents role is really the spin-off.

4 PARASITIC RADARS

Here, parasitic radars are taken to mean radar systems relying on third-party transmissions, without a transmit capability of their own. The primary advantage, of course, is the saving of the transmit power, which is generally much the largest element in the satellite power budget.

In principle, it is possible to envisage parasitic versions of almost any type of radar, including altimeters, across-track interferometers and along-track interferometers. In practice, the options are obviously constrained by the availability of suitable transmitters. The main options for parasitic radar transmitters are:

- third-party radars of the same type (with conventional radar reception);
- broadband CW noise-like sources (measuring the path difference by cross-correlating the direct and reflected path signals).

Some options are given below.

4.1 GPS ALTIMETERS AND SIMILAR

GPS altimetry seems to be the most promising parasitic radar concept, exploiting the bistatic echoes of GPS signals specularly reflected from the sea surface. Global Positioning System (GPS) signals are a special case of broadband noise-like transmissions, which are specifically designed for time/path difference estimation.

Advantages include the number and global availability of transmitters, fairly high transmit powers, the possibility to use off-the-shelf receivers, a built-in mechanism to synchronise to transmitters and SSTL background experience. Potential problems include the link budget, discrimination of the wanted surface reflections from the directly received signals and the achievable height accuracy and precision. Many of the issues relevant to conventional altimeters, e.g. orbit determination and path corrections, also apply. Another issue is the rather disjointed coverage likely to be obtained given a LEO receiver and a set of MEO transmitters.

GPS altimeters are considered in more detail in the separate SSTL technical note.

In principle, similar bistatic specular altimetry might be performed using the transmissions from other CW transmitters. Transmissions that might potentially be useful include digital television satellite broadcasts from GEO. These have wider bandwidths than GPS and so could provide better range precision, but there are drawbacks too. Unlike GPS, COTS receivers are not available so special-to-type cross-correlators would have to be implemented. Also, the TV signals may not always be suitable to provide unique time-delay measurements by cross-correlation. However, the biggest drawback with TV transmissions is probably the spatial coverage, as they are inevitably directed to continents rather than oceans.

4.2 OTHER PARASITIC ALTIMETERS

Clearly, one could put additional bistatic receivers near 'big' altimeters such as Envisat RA-2 or Jason. Receive-only systems could provide additional surface height measurements and be more affordable than complete altimeters. Savings could be made in:

- The altimeter itself. The power amplifier and circulator (and maybe the receiver protection circuitry) can be removed, but the dish and the receiver (and hence the pulse generator) must be retained. Hence the mass savings may not be very great, perhaps ~ 15–20%. However, the power savings are significant.

- The microwave radiometer. This can be omitted entirely, instead obtaining the water vapour measurements from the host.
- Ancillary equipment for orbit determination. It might be appropriate to determine the secondary receiver's position relative to the transmitter, e.g. using differential GPS, rather than absolutely. Apart from potential savings on mass and power, this approach could well provide more accurate surface slope measurements.

However, coverage is severely limited by the host's transmit beam footprint. The bistatic receiver must be close to the transmitter and the bistatic footprint track must be close to the monostatic one. The additional information would be much more useful if the second receiver were offset across-track, in which case it could directly measure the across-track surface slope. Assuming the parasitic receiver performed ideally, the achievable height accuracy would be similar to the host altimeter's height accuracy. The maximum across-track baseline would be about half the transmit beam footprint width along-track (with one parasitic receiver). Bistatic altimetry aligned along the transmitter's track would not produce significant new information, just a revisit of the host's track seconds later.

Practical issues include:

- Precise pulse compression, which requires extremely good long-term frequency stability on the part of both satellites. Failing that, the bistatic receiver might be able to analyse intercepted host's transmissions in order to derive the pulse parameters. In extremis, the receiver might be able to capture the transmit pulse as a replica to cross-correlate against the reflected signal (but that implies sampling at the full pulse bandwidth, not deramping).
- Precise pulse timing. In the absence of specific cooperation from the transmitter, this again might imply a need to intercept the host's transmissions, plus an accurate knowledge of the relative position.

  Note that, with a chirped transmit signal, it is not possible accurately to derive both the pulse centre frequency and the transmit time by intercepting and deramping the direct-path transmissions. At least one would need to be known. Otherwise, the timing might have to be derived from precise observations of the rising edge of the pulse. The latter approach would require fast sampling and a good SNR for the direct path signal, which may not always be the case.
- Formation-keeping, given two quite different (or in the case of a small receiver alongside Envisat, very different) satellites. The safety implications of flying a receiver quite close to the transmitter would be significant, both practically and politically (e.g. who pays if…). As noted above, it is desirable to operate the bistatic altimeter in an across-track configuration.

  Because of the way that inertial formations appear to rotate about their centre as they orbit the Earth, at least two receive-only satellites would be needed in order to provide an across-track baseline at all times. Also, such a formation would need to be inclined across-track (see §3.3.1d), and for half the orbit the receiver would be slightly above the transmitter (possibly precluding interception of the direct path transmit pulse).
- Other issues for monostatic altimeters, e.g. the need for accurate orbit knowledge, are also applicable here.

Parasitic altimetry is feasible in principle, given sufficiently precise frequencies and times for the transmit pulses. In practice, it is much more likely to be successful if the transmitter is cooperative. Thus, it is better to consider the inclusion of additional bistatic receivers with future ‘big’ altimeters during their design phase, rather than adding receivers to already-operational altimeters.

4.3 PARASITIC RADAR INTERFEROMETERS

In principle, parasitic radars could exploit transmissions from broadband CW transmitters or from third-party RARs or SARs. In practice, the use of broadband CW transmitters for imaging radars is largely precluded by consideration of the link budget for available transmitters (at least at present):

- Specular reflections from the ocean surface may be sufficiently intense. However, no range resolution is available around the stationary point, so a specular reflection is only suitable for bistatic altimetry (see §4.1) (plus a scatterometry measurement at a single spot in a relatively unfavourable geometry). However, it might be possible to perform interefometry with two parasitic receivers observing the specular return, see §4.3.1.
- Away from the specular point, range resolution is possible but the scattered signals are orders of magnitude smaller precluding their observation.

Otherwise, parasitic receivers must exploit the returns from other imaging radars, see §4.3.2.

4.3.1 GPS Interferometry

As just noted, this is probably only possible about the specular point. Even then, signal-to-noise may be a problem.

Along-track interferometry requires observations from two satellites from the same position in space but milliseconds apart (~ 50 ms for GPS frequencies). Standard COTS GPS receivers provide measurements at fixed update rates and would not be able to match the precise interval between satellites[17]. However, given an adequate update rate, it might be possible to interpolate the GPS carrier phase measurements to the required time. Depending on the signal-to-noise, it would probably then be necessary to sum up a number of independent looks to achieve an adequate phase difference accuracy. If this were successful, the system would provide a measurement of the radial component of the current along a single line. This does not seem to be a particularly good return on the investment of two satellites.

Across-track interferometric measurements may be possible, but with little or no significant swath do not provide useful information.

4.3.2 Other Space-Based Radars

Generally, interesting transmitters are radars that would be operational most of the time, e.g. altimeters, operational wind scatterometers (such as Metop’s ASCAT) and ‘global monitoring’ SARs. Other SAR modes could also be exploited, but no existing transmitters are able to support extended operation. Possible options are as follows:

[17] Alternatively, the orbital separation between satellites could be chosen to match the GPS update rate, but this would only work at an instant, as the geometry would change continuously for a mixed LEO/GEO bistatic scenario.

a) 'Big' altimeters

Altimeter transmissions do not seem to offer useful possibilities for parasitic altimetry. The nadir-looking geometry is no use for ATI or XTI, and the altimeter swath width is too narrow for useful XTI as well. A free-flying second antenna for across-track interferometric altimetry (c.f. §2.3.2) is also impossible, because the spacing would have to be too large and the phase would be hopelessly aliased.

b) SARs

It would be possible in principle to put an additional receiver or receivers[18] across-track or offset along-track from a third-party SAR. Unless the third-party cooperates in the reception and processing, at least two passive receivers are required to perform interferometry[19].

Exploiting a third-party SAR transmitter would provide savings in several ways:

- Most importantly, the large transmit power requirement is eliminated, and a large part of the batteries and solar array with it. This also avoids the associated serious heat dissipation problem.
- The antenna or T/R module architecture can be simplified, by elimination of the transmit phase shifter(s), HPA(s) and circulator(s).
- It might be possible to make the receive-only antenna smaller, by relying on the transmit antenna pattern to provide the bulk of the ambiguity rejection. This was done for SRTM, where the secondary X-band antenna at 6 m was only half the length of the primary one.

Of course, the receiver, data-handling and down-linking aspects are unchanged. Overall, a receive-only SAR satellite will probably be about half the mass of a full SAR, maybe even less.

The achievable performance and many of the issues for parametric interferometers should be similar to the standard interferometry case, see §3. The problems of synchronisation and formation keeping are basically the same as for parasitic altimeter receivers, §4.2.

c) RARs

It would also be possible to put an additional receiver or receivers with a third-party RAR (e.g. a scatterometer). However, the savings in transmit power and antenna costs in the case of a RAR would be relatively small, and in general would not justify the additional complexity of operating in a parasitic mode. Instead, a RAR formation concept should provide its own transmit capability. In principle, some of the satellites in such a formation could be parasitic (receive-only). In practice, it will probably be preferred to have all satellites identical, able to share the load and providing redundancy.

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[18] As before, consideration of formation motion implies the need for three or more satellites to provide an across-track baseline all round the orbit.

[19] In that case, the receivers must be close to one another but they might not necessarily need to be near the transmitter. A modest along-track offset from the transmitter would greatly mitigate safety concerns.

However, operation of a pair of receivers in a very different orbit from the transmitter will certainly be more complex. Moreover, ATI may be invalidated completely or significantly degraded, as the requirement for two images from the same position at different times cannot be met. XTI might well become contaminated with an ATI component.

5 CONCLUSIONS

A number of technological options to provide direct or indirect measurements of ocean currents from space have been identified. These are summarised as follows:

- Radar altimeters have provided the most effective (albeit indirect) means of measuring ocean currents to date and will undoubtedly remain important in the future. Their principal drawback is the sparse spatial and temporal coverage provided. This could be ameliorated by providing additional radar altimeter satellites. The existing satellite altimeters, such as Jason, are precise but quite large. Rather than launching a few more 'big' altimeters, it would be preferable to launch more, smaller altimeters with limited capabilities. The French AltiKa Ka-band altimeter [6] concept, for example, looks promising for such a role. The smaller altimeters would fill in between the few big systems and could be cross-calibrated against those.
- Two new advanced processing techniques are proposed for the SIRAL instrument on Cryosat [7]. For ocean observations, Doppler beam sharpening (aka aperture synthesis) offers improved along-track resolution and sensitivity for a small increase in instrument complexity. On the other hand, SIRAL's across-track interferometry mode has no obvious use over the ocean but doubles the number of antennas required.
- Bistatic radar altimeter formations such as the proposed 'WITTEX Bistatic' [9] do not seem to offer any nett benefit relative to a formation of similar but simpler monostatic altimeters. However, the deployment of an additional parasitic bistatic receiver in formation with another altimeter could provide complementary measurements of the across-track surface slope from a small satellite. Several small satellites would actually be required in order to measure across-track slopes at all latitudes.
- Lidars provide similar measurements to microwave altimeters. The instrument can be smaller, but the lack of European experience and the susceptibility to cloud are drawbacks.
- Along-track interferometry (ATI) using Synthetic Aperture Radar (SAR) is a very promising technique to measure current fields over a wide swath directly, see §3.2.5. A single SAR could provide relatively fine resolution over a narrow swath in the coastal zones and coarser resolution over a wider swath in mid-ocean, by exploiting strip-map and scanSAR modes. The major problem is that space-based SARs are necessarily big, power-hungry instruments, and ATI needs two of them. On the other hand, SAR data has many applications beyond ocean currents, and SAR ATI may be exploited for surveillance of moving targets on land. These additional applications may justify the high costs of a SAR ATI mission. An option is to fly a second receiver (maybe just a smaller parasitic receiver) behind an existing / planned SAR satellite (e.g. TerraSAR), but this may be difficult if the primary transmitter is not fully cooperative.
- Across-track SAR interferometry (XTI) can potentially provide height profiles over a wide swath. However, the performance may not be adequate for the ocean surface slopes anticipated (see §3.3.2) or robust enough. Also, at least three satellites would be required in order to operate at all points round the orbit.

- Real Aperture Radar (RAR) can also be used to observe the open oceans, although the resolution is much coarser. The major advantage of a RAR is that the instrument is very much smaller and much lower power than a SAR. A RAR ATI system could provide good currents over a wide swath but only at a very limited resolution, see §3.4. A modular RAR formation could also provide wind fields and maybe rainfall fields over the ocean, see §3.5; this might help to justify a mission or demonstrator.
- The RAL study [2] concluded that the addition of a Sea Surface Temperature (SST) sensing capability to a radar altimeter mission would be particularly beneficial. ATSR is considered appropriate, for reasons of cost and risk, although its limited swath means that several satellites might be needed.
- The SSTL study [3] concluded that GPS reflectometry holds great promise as a future tool of ocean science. There are significant requirements on the space platform, including a large high-gain antenna, strict orbit knowledge and tight pointing and tracking requirements. Nevertheless, reflected GPS signals have been detected from space, and reflected GPS signals have been successfully used to determine wind speed, significant wave height and altitude to within 1 cm from ground experiments. SSTL and others are currently very active in this area, but it will be several years before a useable system comes into being.

Whether any or a combination of these options could be cost-effective for an Ocean Currents Service Mission will be assessed in Work Package 4 of the study.

ANNEX A

AN ILLUSTRATIVE REAL APERTURE RADAR DESIGN

A.1 INTRODUCTION

This annex describes a "straw-man" Real Aperture Radar (RAR) with possible applications to radar interferometry of the ocean, which is a compromise between performance and instrument size. It is not a specific proposal of a "suitable" instrument for any particular purpose, but is intended to illustrate…

- typical instrument and complexity;
- typically achievable performance; and,
- available trade-offs between complexity and performance.

For the ocean currents application, two similar radars might perhaps be used for either across-track or along-track radar interferometry. However, only the single, basic instrument is considered in this annex.

A.2 BASELINE INSTRUMENT

A side-looking real aperture radar is considered, Figure A-1.

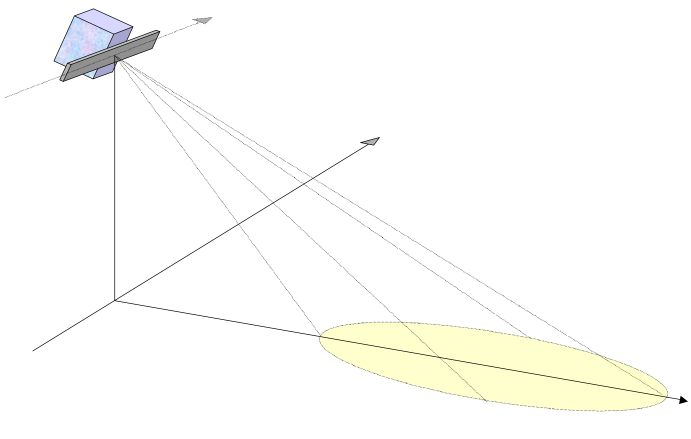

Figure A-1. Basic Geometry

For a RAR, the resolution in azimuth is determined by the azimuth beam-width and hence by the antenna length along-track and the wavelength. The antenna length is constrained so, even with the longest acceptable antenna and a relatively high frequency, the azimuth resolution will be quite coarse. The range resolution is pulse-limited and very much better. For a RAR, there are no azimuth ambiguities and the pulse repetition frequency can be set low enough to eliminate range ambiguities as well. Then a broad beam in elevation can be used to give a wide swath. This results in a long, thin antenna aligned along-track.

The transmit power requirement must ultimately be determined by consideration of the link budget, i.e. the signal-to-noise ratio. However, chirp transmissions and pulse compression can improve the process signal-to-noise for a given resolution and peak RF power.

A.2.1 Analysis

An analysis based on the above considerations and a typical space-based radar geometry is given below. The inputs, indicated by ">>" at the start of the line, have been contrived to give a reasonable compromise between instrument complexity and performance (including adequate signal-to-noise for the very low backscatter cross-section assumed). Various performance and load figures are derived. The equations used are also summarised.

	Parameter	Value	Units	Symbol / Formula
>>	Satellite Orbit Height	800	km	hs
-	Earth's radius	6378	km	Re
-	Gravitational constant μ	4.0E+14		μ
	Orbital Speed	7465	m/s	$Vs = \sqrt{(\mu/(Re+hs))}$
	Ground Speed	6633	m/s	$Vg = Vs \times Re/(Re+hs)$
>>	Incidence Angle	45.0	°	θ
	Elevation from Nadir	38.9	°	$\alpha = \mathrm{asin}(\sin(\theta) \times Re/(Re+hs))$
	Ground Range	676	km	$Rg = Re \times (\theta - \alpha)$
	Slant Range	1074	km	$Rs = Re \times \sin(\theta - \alpha)/\sin(\alpha)$
>>	Frequency	9.8	GHz	f0
-	Speed of Light	3.0E+08	m/s	Clight
	Wavelength	0.031	m	$\lambda = Clight/f0$
>>	Antenna Length	1.5	m	La
	Azimuth Beamwidth	1.17	°	$BWa = \lambda/La$
	Azimuth Footprint	21.9	km	$BFa = Rs \times BWa$
	Azimuth Dwell-Time	3305.5	ms	$BDa = BFa/Vg$
	Min PRF for Cont. Sampling	0.30	Hz	$PRF1 = 1/BDa$
>>	Antenna Height	0.1	m	Ha
	Elevation Beamwidth	17.54	°	$BWe = \lambda/Ha$
>>	Boresight Elevation	40.0	°	αA
	Min Elevation	31.2	°	$\alpha 1 = \alpha A - BWe/2$
	Max Elevation	48.8	°	$\alpha 2 = \alpha A + BWe/2$
	Min Incidence	35.7	°	$\theta 1 = \mathrm{asin}(\sin(\alpha 1) \times (Re+hs)/Re)$
	Max Incidence	57.8	°	$\theta 2 = \mathrm{asin}(\sin(\alpha 2) \times (Re+hs)/Re)$
	Min Ground Range	497	km	$Rg1 = Re \times (\theta 1 - \alpha 1)$
	Max Ground Range	1008	km	$Rg2 = Re \times (\theta 2 - \alpha 2)$
	Min Slant Range	958	km	$Rs1 = Re \times \sin(\theta 1 - \alpha 1)/\sin(\alpha 1)$
	Max Slant Range	1334	km	$Rs2 = Re \times \sin(\theta 2 - \alpha 2)/\sin(\alpha 2)$
	Ground Swath Width	510	km	$Rgw = Rg2 - Rg1$
	Slant-Range Swath Width	376	km	$Rsw = Rs2 - Rs1$
	Swath Receive Period	2.51	ms	$T2swath = 2 \times Rsw/Clight$
	Antenna Area	0.15	m²	$Aa = La \times Ha$
	Antenna Gain	33.0	dBi	$Ga = 4 \times \pi \times Aa/\lambda^2$
	Slant Range to Limb	3293	km	$Rlimb = \sqrt{((Re+hs)^2 - Re^2)}$
	2-Way Travel Time to Limb	22.0	ms	$T2limb = 2 \times Rlimb/Clight$
	Max PRF for No Range Ambs	45.5	Hz	$PRF2 = 1/T2limb$

>>	Pulse Bandwidth	0.05 MHz	Bp
	Slant-Range Resolution	3.00 km	ρs = 0.5×Clight/Bp
	Ground-Range Resolution	4.24 km	ρg = ρs/sin(θ)
>>	Pulse Duration	10 ms	Tp
>>	Pulse Repetition Frequency	5 Hz	PRF
	Pulse Tx Duty Cycle	5.0%	TxDutyCycle = PRF×Tp
	Receive Duration	12.5 ms	Trx = T2swath+Tp
	Receive Duty Cycle	6.3%	RxDutyCycle = PRF×Trx
	Pulse BT Product	500	BpTp = Bp×Tp
>>	Rx Oversampling Factor	125%	Krx
>>	Rx Bits/Sample	8	Nrx
	Rx Data Rate	61 Kbits/s	bps = PRF×Trx×(2×Krx×Bp)×Nrx
>>	Peak Transmitted RF Power	50 W	Pt
	Average Transmitted RF Power	2.5 W	Ptav = Pt×TxDutyCycle
>>	Power Conversion Efficiency	20%	Epc
	Tx Electrical Power Load	12.5 W	Pteav = Ptav/Epc
>>	Antenna Noise Temperature	300 K	ANT
>>	Total Receiver Noise Figure	5 dB	NF
>>	Normalised Cross-Section σ0	-30 dBm^2/m^2	σ0

Link Budget

Peak Transmit Power	+17.0 dBW
Transmit Beam Gain	+33.0 dB
Receive Beam Gain	+33.0 dB
Normalised Cross-Section σ0	-30.0 dBm^2/m^2
Resolution Cell, Azimuth	+43.4 dBm
Resolution Cell, Ground-Range	+36.3 dBm
Cos(σ) Incidence Angle Factor	-1.5 dB
λ^2	-30.3 dBm^2
$1/(4\pi)^3$	-33.0 dB
1/R4	-241.2 dB/m4
Signal from Resolution Cell	-173.3 dBW

Boltzmann's constant, 1.381e-23	-228.6 dBWsK^{-1}
Bandwidth	+47.0 dBs^{-1}
Antenna Temperature	+24.8 dBK
Noise-Figure	+5.0 dB
Noise	-151.8 dBW

Receiver Signal:Noise Ratio	-21.4 dB
BT Processing Gain	+27.0 dB
Processed Signal:Noise Ratio	+5.6 dB

The standard equation used for the link budget is

$$\left(\frac{S}{N}\right)_{processed\ resolution\ cell\ \rho_{az}\times\rho_g} = \frac{P_{tx}G_a^2\lambda^2\cdot\sigma_0\rho_{az}\rho_g}{(4\pi)^3R_s^4\cdot k_BB_pT_{antenna}N_F}\times B_pT_p$$

Losses are not explicitly separated, but are incorporated in the Tx power conversion efficiency and the Rx noise figure.

A.2.2 Discussion

Technology. The baseline system analysed above is generally consistent with a small-satellite implementation:

- The antenna, at 1.5 m long by 0.1 m high, is relatively small. Being passive, low-bandwidth and unsteered, a simple printed patch array and strip-line corporate feed would be adequate and the mass and cost could be low. However, the mechanical tolerances at X-band (viz. planarity to ~ 1 mm, i.e. << the wavelength) are tight, so adequate stiffening is important. Even so, the antenna might weigh of the order of ten kilograms, including the mechanical support[20]. At 1.5 m, it might just be possible to launch the satellite with the antenna already fixed in the operating position. If the antenna has to be folded for launch, the necessary deployment mechanisms and RF connectors will add some extra mass and complexity.
- The peak transmitted RF power, at 50 W, is modest. Even allowing for some losses in the transmit path to the radiating elements, solid-state power amplifiers (rather than TWTs) are easily adequate. The average electrical power load of the transmitter, at about 12.5 W, is modest.
- The pulse generator and receivers will increase the total payload a little further, but are not difficult as the bandwidth so small.
- The data rate is estimated as 61 kbits/s. If the radar were operated continuously, the accumulated data would comprise 644 Mbytes/day. At 800 km altitude, a satellite would be within an 80° cone-of-cover above a ground station in northern Britain for approximately 50 minutes per day – see Figure A-2. Then the required down-link data rate would be approximately 1.7 Mbit/s. Data would need to be stored on-board for up to about 6 orbits between ground-station passes, implying an on-board storage requirement of the order of 270 Mbytes. Hence, none of the data handling requirements are prohibitive.

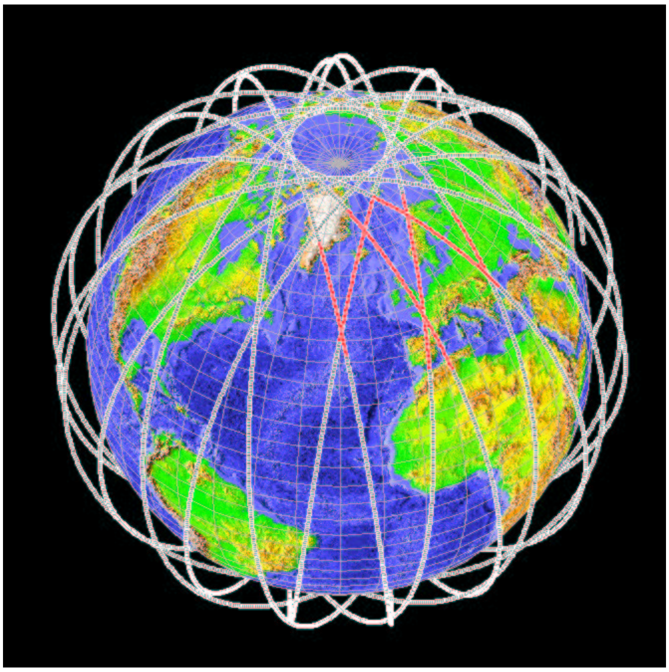

Figure A-2. Example Satellite Tracks (800km altitude, 80° inclination) and Downlink Periods

The data rate could be reduced further by implementing on-board pulse compression, either by using a deramp receiver (c.f. altimeters, ASCAT) or by on-board digital processing after reception. Given the limited number of samples per receive, pulse compression would require only ~0.5 Mflop/s and could reduce the data rates and volumes to ~20% of the above values by eliminating the pulse replica guard-bands.

[20] A wave-guide antenna could also be considered. Although the antenna itself would be heavier, it would also be inherently stronger, and so less support structure would be required.

Performance. The system parameters above were chosen to give adequate signal-to-noise for all sea-states at low to moderate incidence angles. The one performance aspect that is seriously limited is the azimuth resolution. This is equal to the beam footprint, which is of course determined by the constrained antenna length. At ~22 km, the resolution would effectively preclude use in the coastal zones and would be insufficient to resolve some open-ocean features. Lengthening the antenna, or moving to higher frequency, will improve the azimuth resolution (see §A.3) but the scope is limited.

Although the pulse repetition frequency PRF is quite low, successive azimuth footprints are highly overlapped, giving ~17 pulses at each along-track position. This would provide some noise averaging and, given the decorrelation times of the ocean, multiple independent looks to enable averaging of speckle.

The range resolution (3.5–5.1 km depending on the position across the swath) for the chosen parameters is significantly better than the azimuth resolution, but could readily be improved further if required. Instead of range resolution, the available pulse bandwidth could be used to obtain several independent looks at more nearly square resolution cells.

The swath width of about 500 km is limited by the elevation beamwidth in the design in §A.2.1. This is broadly compatible with global coverage in about 6 days, see Figure A-3. (In fact, the 800km altitude, 80° inclination orbit shown in Figure A-2 repeats in about 5 days 23 hours, and so would be a good match to this swath width.) A constellation of several satellites could be used to provide global coverage in a shorter term: 6 satellites for 1 day, 3 for 2 days or 2 for 3 days.

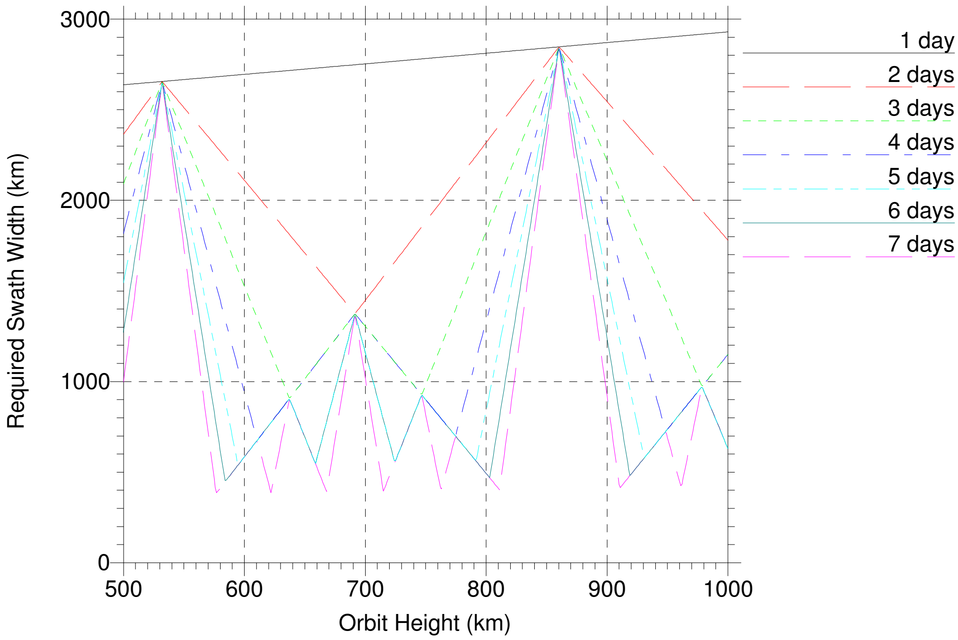

Figure A-3. Swath Width required for Global Coverage with a Single Satellite, 80° inclination

A.3 AVAILABLE TRADE-OFFS

The design in §A.2.1 provides a reasonable small-satellite, real aperture radar but was not designed to meet any specific criteria. There is scope to trade-off many parameters to tailor the design further to a particular application. The main trade-offs that could be considered are listed in the following table.

Design Change	*Impacts, positive and negative*
Increase frequency f	☺ Improves azimuth resolution ($\rho_a \propto 1/f$) ☺ Improves signal-to-noise ($\propto f$) ☹ Reduces swath width ($\propto \sim 1/f$) ☹ Tightens antenna mechanical tolerances ☹ Increases susceptibility to interference from rain etc.
Increase antenna length ℓ	☺ Improves azimuth resolution ($\rho_a \propto 1/\ell$) ☺ Improves signal-to-noise ($\propto \ell$) ☹ Increases demands on antenna mechanical stability ☹ Complicates accommodation and deployment ☹ May complicate spacecraft AOCS etc.
Increase antenna height h	☺ Improves signal-to-noise ($\propto h$) ☹ Reduces swath width ($\propto \sim 1/h$)
Increase bandwidth B_p	☺ Improves range resolution ($\rho_r \propto 1/B_p$) or number of range looks at constant resolution ($\propto 1/B_p$) ☹ Increases data rate and volume ($\propto B_p$) ☹ Decreases signal-to-noise ratio ($\propto 1/B_p$)
Increase pulse length T_p	☺ Improves signal-to-noise ratio ($\propto T_p$) ☹ Increases Rx data rate ($\leq\propto T_p$) or on-board processing requirement ($\leq\propto T_p$) ☹ Increases average power demand ($\propto T_p$)
Increase transmit power P	☺ Improves signal-to-noise ratio ($\propto P$) ☹ Increases peak and average power demand ($\propto P$)
Increase PRF f_p	☺ Improves noise averaging (and maybe speckle averaging, depending on the PRF c.f. the decorrelation time) ☹ Increases data rate (unless on-board averaging is done) ☹ Increases average power demand ($\propto f_p$)

Table A-1. Main Trade-Offs for a Real Aperture Radar

ANNEX B

AN ILLUSTRATIVE SYNTHETIC APERTURE RADAR DESIGN

B.1 INTRODUCTION

This annex describes a straw-man Synthetic Aperture Radar (SAR) with possible applications to radar interferometry of the ocean. It is not a specific proposal of a "suitable" instrument for any particular purpose, but is intended to illustrate…

- typical instrument and complexity;
- typically achievable performance; and,
- available trade-offs between complexity and performance.

SARs can achieve very fine resolutions. However, for the ocean currents application, the need is for more moderate resolution, wide coverage and continuous operation. Another required, or at least extremely desirable, feature is affordability. Thus, the design drivers are quite different from those typically used in ESA programmes and studies, where high quality tends to be paramount. However, in practice, any space-based synthetic aperture radar is inevitably a complex and relatively expensive instrument.

B.2 SOME GENERAL SAR DESIGN PRINCIPLES

SARs are sufficiently complicated that detailed analysis software is generally required to assess and adjust designs. However, there are a number of basic principles which can be used to guide the initial design:

- Achievable azimuth resolution. The finest is azimuth resolution that can be achieved is equal to about half the along-track antenna length. Thus, for example, a SAR with a 10 m long antenna can achieve, at finest, about 5 m single-look along-track resolution.
- Reduced azimuth resolution modes. Instead of the ultimately finest resolution, it is possible to form multiple independent azimuth looks at lower resolution, i.e. N_L looks with N_L times poorer azimuth resolution. Alternatively, ScanSAR mode[21] can be used to cover a wider total swath at lower resolution, forming N_{ss} subwaths with (N_{ss}+1) times poorer resolution. A ScanSAR system is likely to be appropriate for most oceanographic purposes.
- Minimum PRF. In order to sample the synthetic aperture adequately, a SAR needs to transmit and receive at least two pulses per antenna length. Thus, for a 10 m antenna orbiting at about 7000 m/s, the minimum PRF is 2×7000/10 = 1400 Hz. Failure to do this will introduce significant *azimuth ambiguities*, i.e. signals from different positions along-track superimposed.

[21] This also requires an antenna with an electronic steering capability in azimuth.

- Range ambiguities. The minimum PRF requirement for a SAR, combined with the long operating ranges for a satellite system, means that there will be multiple pulses in flight and reflecting from the Earth at the same time. The elevation antenna pattern needs to be sufficiently directional to select the required echo and suppress the returns from the *range ambiguities* – see Figure B-1.

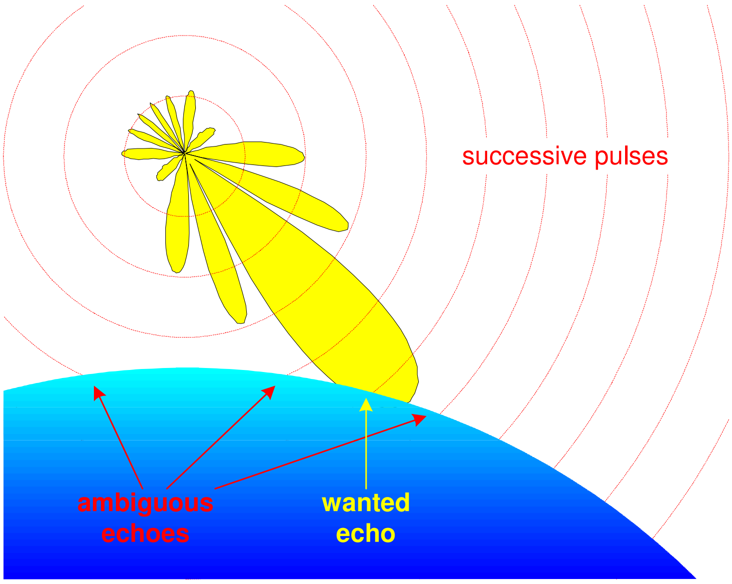

Figure B-1. Range Ambiguities and Antenna Pattern

- Minimum Antenna Area. In order to simultaneously suppress both the azimuth and range ambiguities, the antenna area is constrained as follows:

  The PRF is $f_p \geq 2V_s/L$. Successive pulses are separated by $C/2f_p$ in one-way slant-range and the range ambiguities are therefore ~ $C/2f_p r\tan\theta$ radians apart in elevation, see Figure B-2.

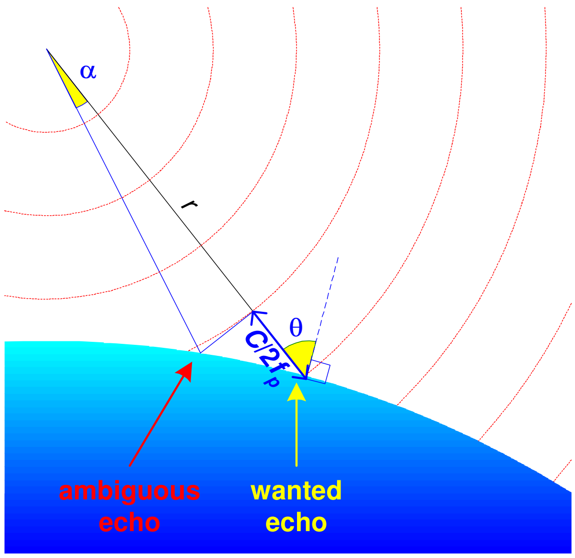

Figure B-2. Range Ambiguity Spacing in Elevation

To obtain the wanted returns but suppress the adjacent range ambiguities, the elevation beam peak-to-null then needs to be ~ $C/2f_p r\tan\theta$, so

$$\frac{\lambda}{H} \leq \frac{C}{2f_p r\tan\theta} \leq \frac{C}{2(2V_s/L)r\tan\theta}$$

$$HL \geq \frac{4V_s}{f_0} r\tan\theta$$

The minimum antenna area depends critically on the maximum operating incidence θ, and is inversely proportional to frequency. The approximate minimum antenna area is summarised in Figure B-3.

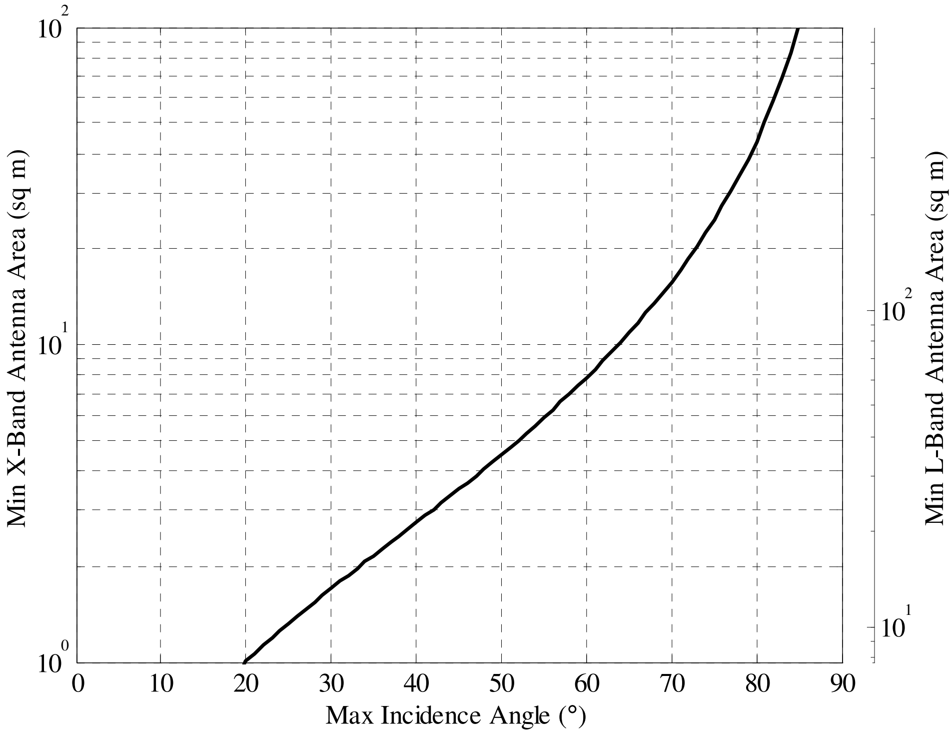

Figure B-3. Minimum Antenna Area versus Operating Incidence, 800 km Altitude

A wide-swath ScanSAR system, which would typically be appropriate for the ocean currents application, will operate out to relatively high incidence angles – e.g. 20°–50° incidence for a 500 km swath from 800 km altitude (see Figure B-4). Then an X-band antenna should be at least 3–4 m^2 (and an L-band antenna 30 m^2 or more). Note that even larger antennas areas may be required in practice, in order to provide useful coverage over a finite subswath width and the associated, faster roll-off towards the range ambiguities.

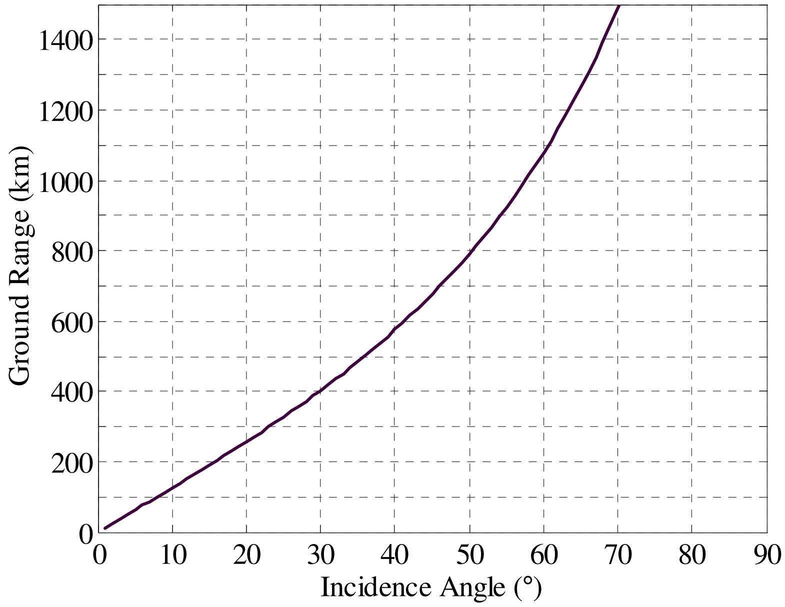

Figure B-4. Ground Range versus Incidence Angle, 800km Altitude

B.3 AN EXAMPLE SAR DESIGN

This subsection presents an outline design of a SAR system with the ocean currents application in mind. In order to keep the system small, an X-band SAR is suggested. Also, a wide swath at modest resolution is considered, implying a system optimised for ScanSAR mode and therefore maybe rather different from other SAR instruments/concepts designed primarily for high resolution. The design was performed using the SEA/Dornier "NextPerf" software, and is a pragmatic compromise between performance (especially sensitivity and ambiguity levels) and instrument complexity (power, antenna size, etc.)

Seven scanSAR subswaths were used to cover 20°–50° incidence with 100 m resolution and 4 looks. Table B-1 and Table B-2 summarises the main instrument parameters.

Parameter	*Value*	*Comments*
Operating Frequency Primary Operating Mode	9.8 GHz ScanSAR	X-band, for relative compactness for low resolution and wide swath
Orbit Height Orbit Inclination	800 km 80 °	

Antenna Length	7 m	trade-off of antenna dimensions and PRFs to control range and azimuth ambiguities
Antenna Height	1 m	
Azimuth Beamforming	fixed	constant amplitude and phase
Elevation Beamforming	electronic	optimised amplitudes and phases
Antenna Boresight Elevation	40°	
Antenna Boresight Yaw	–3.8°	yaw to zero Doppler at calculation latitude
Antenna Losses	1 dB	
Antenna Noise Temperature	290 K	Earth background
Transmit Pulse Duration	30 µs	
Transmit Pulse Bandwidth	see Table B-2	subswath-dependent, → 100 m range res.
Pulse Repetition Frequency	see Figure B-5	subswath-dependent, ~ 2200 Hz
Peak Power	4 kW	RF amplifier output
Transmit Path Loss	1 dB	quite low, assumes row-based architecture
Receive Path Loss	1 dB	
Receiver LNA Noise Figure	1 dB	
Receive Period	see Table B-2	subswath dependent ~ 300 µs,
Number of Doppler Looks	2	
Doppler Look Bandwidth	65 Hz	→ 100 m along-track res.
Azimuth Sidelobe Level	~ –20 dB	
Number of Range Looks	2	
Range Sidelobe Level	~ –20 dB	

Table B-1. Main SAR System Parameters

Subswath	*Rx swath*	$+T_p$ *µs*	B_p *MHz*	*PRF Hz*	*Dwell ms*	*Rate Mbps*	
1	230	30	8.8	2350	21	52	@ 8 bits/complex sample + 20% oversampling
2	322	30	6.9	2250	22	52	
3	352	30	5.6	2125	23	44	
4	352	30	4.9	2175	24	39	
5	328	30	4.5	2210	25	34	
6	332	30	4.2	2125	26	31	
7	286	30	4	2175	27	26	
				total	168	39	weighted average

Table B-2. Subswath Parameters and Data-Rates

Figure B-5 is the 'pulse timing diagram', which is a design aid for the selection of the positions and pulse repetition frequencies for the subswaths. These parameters are constrained by the impossibility of receiving at the same time as transmitting, and by the need for a minimum PRF to avoid azimuth ambiguities. It is then necessary to choose the PRFs and across-track-positions for each subswath to avoid transmit periods. The pulse timing diagram shows, as the red bands, the combinations of PRF and subswath incidence angles that are excluded by transmit periods[22]. The horizontal lines indicate the selected subswaths.

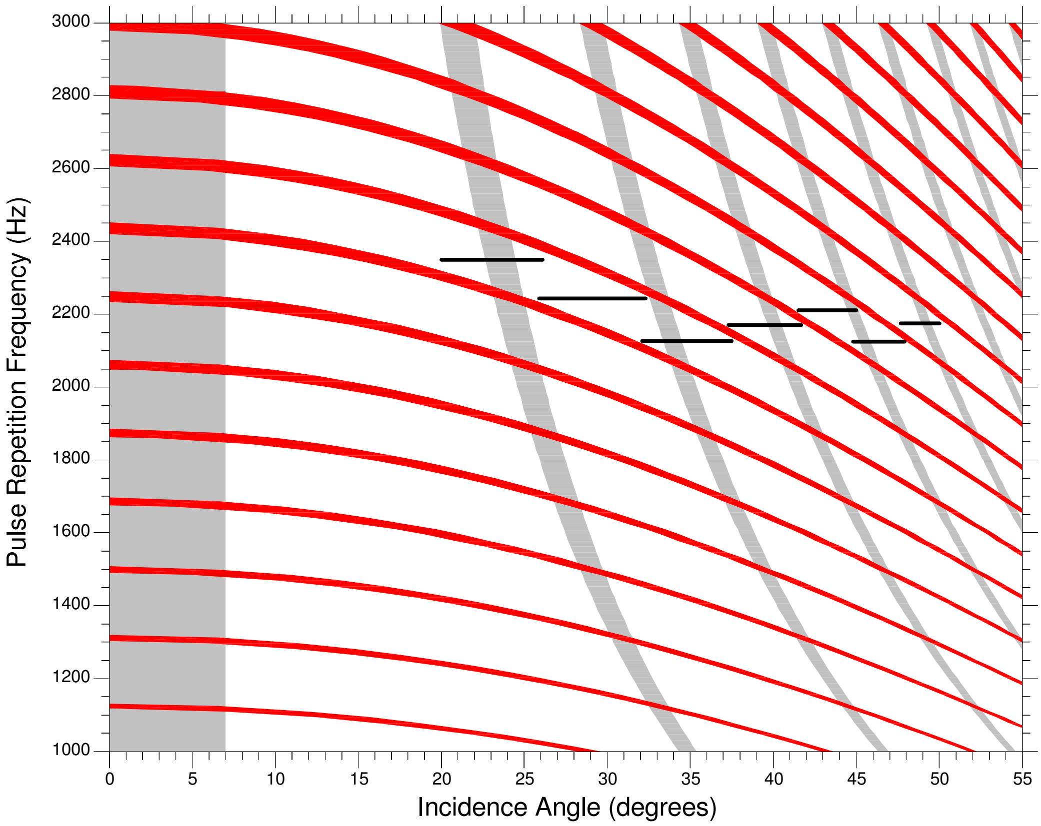

Figure B-5. Pulse Timing Diagram showing all Seven Subswaths

Figure B-6, Figure B-7 and Figure B-8 illustrate the key aspects of the predicted performance of the proposed SAR system.

[22] The pulse timing diagram also shows, in light grey, the combinations of PRF and incidence angles where subswath reception would overlap with the nadir returns from directly below the satellite. For geometrical reasons, nadir echoes can potentially give rise to relatively strong range ambiguities, so it is sometimes decided to choose the swath positions and PRFs to avoid nadir returns. However, this is not the case here, because the elevation beam responses are sufficiently good to suppress the nadir range ambiguities. (The elevation beam patterns, and therefore the antenna height, are actually driven by consideration of the range ambiguities for the farther subswaths, not by the nadir returns.)

Figure B-6 shows the calculated sensitivity of the system, quantified in terms of the noise-equivalent scattering cross-section per unit area, as a function of subswath and incidence angles. Figure B-7 similarly shows the ambiguity levels, including range ambiguities (= echoes offset in time by *m* PRIs), azimuth ambiguities (= echoes offset in Doppler frequency by *n* PRFs), off-cut ambiguities (= echoes offset in both time and Doppler) plus the total of all these contributions.

For a scanSAR system, the performance varies as a function of along-track position, as well as with the across-track position. Figure B-6 and Figure B-7 are actually for the worst-case along-track position (viz. the middle of the processing tile). Figure B-8 shows examples of the along-track variations, for across-track positions in the middle of the nearest and furthest subswaths.

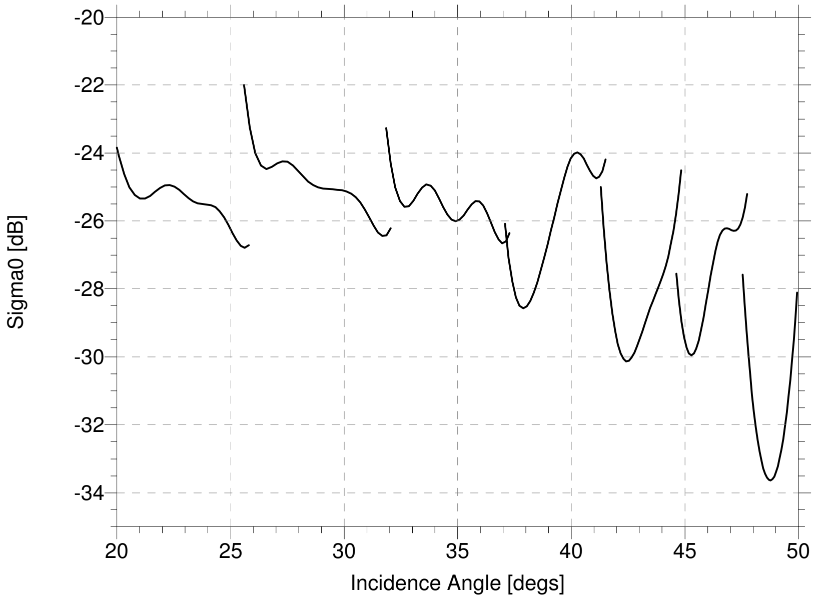

Figure B-6. Noise-Equivalent Sigma-0 versus Subswath and Incidence Angle

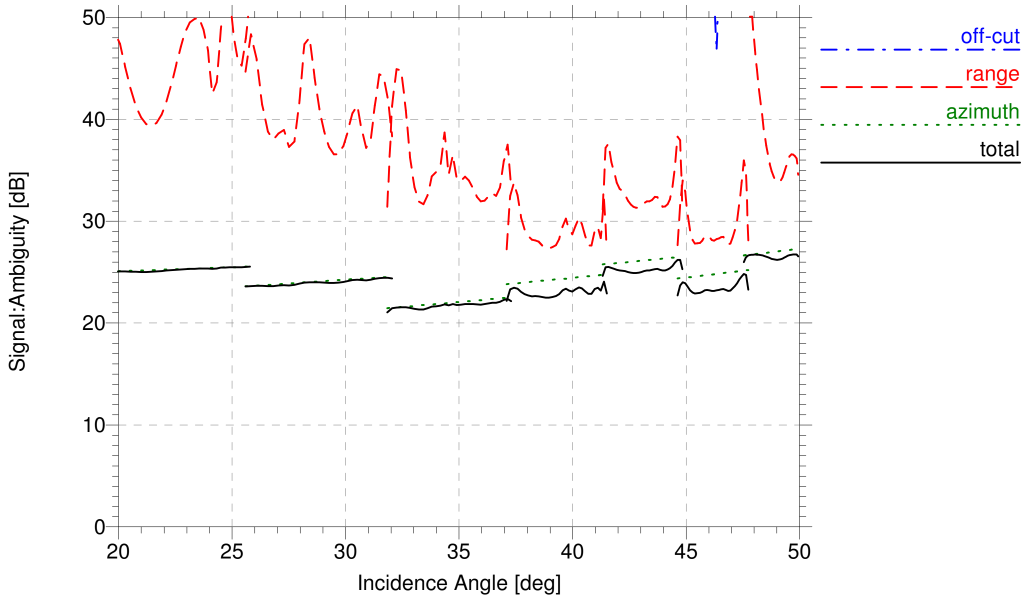

Figure B-7. Ambiguity Levels versus Subswath and Incidence Angle

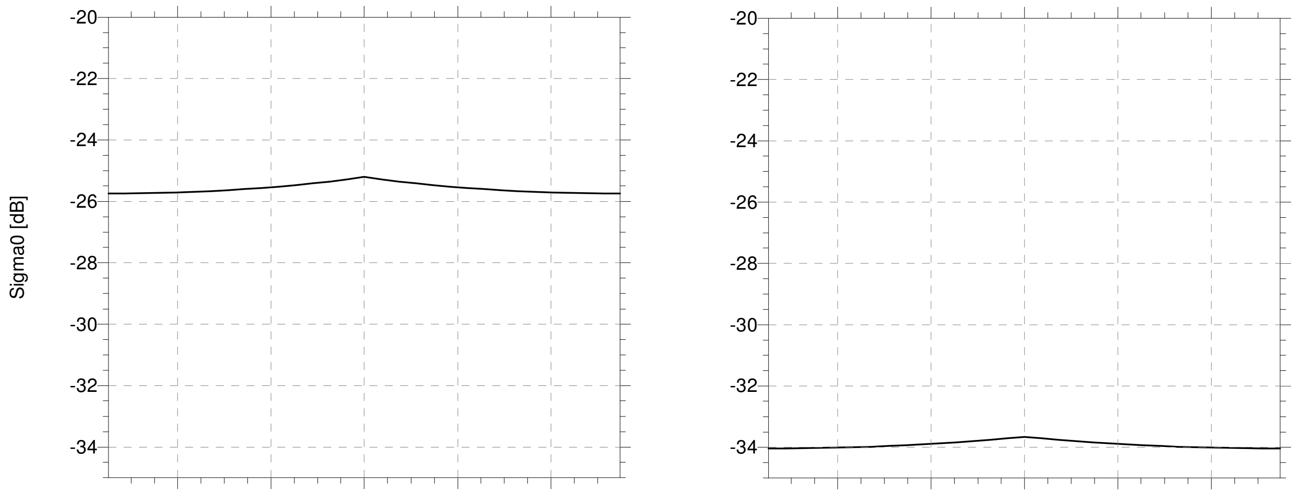

Figure B-8. Along-Track Variation of NESZ for Subswaths 1 (left) and 7 (right)

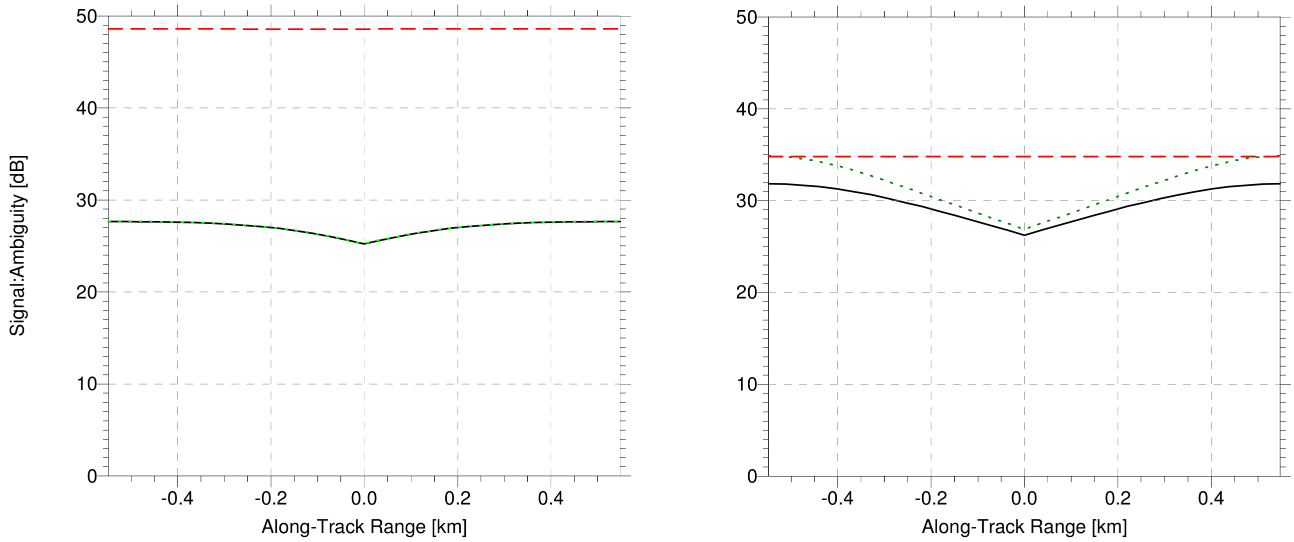

Figure B-9. Along-Track Variation of Ambiguities for Subswaths 1 (left) and 7 (right) (see Figure B-7 for key to lines)

B.4 DISCUSSION

The performance of the SAR instrument concept analysed in §B.3 is broadly consistent with the needs of an ocean-observing instrument:

- The sensitivity (noise-equivalent Sigma-0) provides some margin relative to typical ocean backscatter cross-sections.
- The ambiguity suppression is adequate (though not very high – deliberately, to limit the antenna dimensions).
- The basic resolution (100×100 m × 4 independent looks) is appropriate for coastal zones and pixels can be combined to give very high radiometric accuracy at coarser resolutions (e.g. 100 independent looks at 500×500 m resolution).
- The overall swath width (20–50° at ~800 km altitude, ≈ 530 km ground range) is sufficient for global coverage in less than a week. Figure B-10 and Figure B-11 summarise the coverage for an example orbit. (This repeats after 5 days 23¼ hours and 85 orbits, although in practice a repeat orbit might not be preferred).

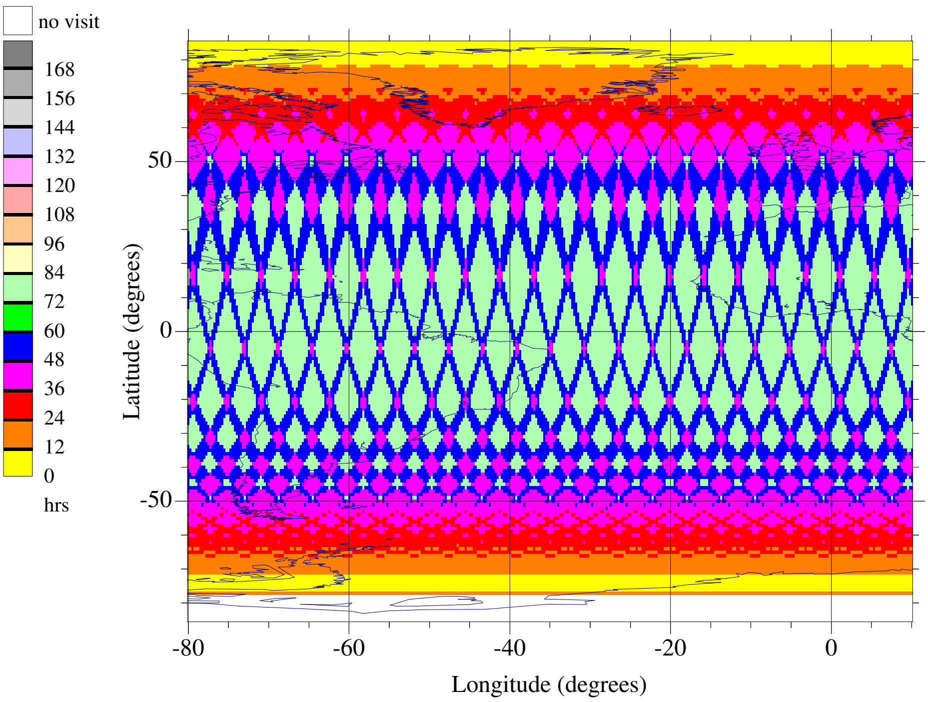

Figure B-10. Mean Revisit Interval (803 km 80° orbit, 20–50° incidence swath)

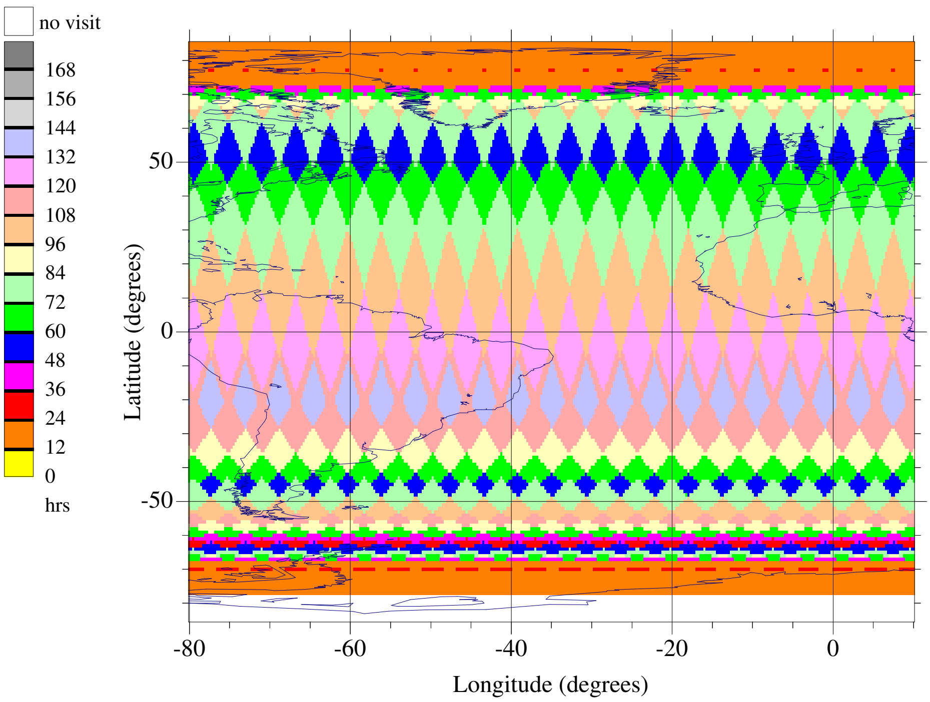

Figure B-11. Maximum Revisit Interval (803 km 80° orbit, 20–50° incidence swath)

While the performance is appropriate, the instrument is too large and demanding to be compatible with a small-satellite approach. Key issues include the following:

- **Antenna Architecture:** Given that elevation steering is required but azimuth steering is not, a "row-based" or "semi-active" antenna architecture is generally preferred (at least where cost is an issue, c.f. Radarsat)[23].

  The row-based architecture provides a modest number (one for each antenna row) of medium-sized RF transmit/receive modules, see Figure B-12. These may be located either immediately behind the middle of the antenna or more remotely within the spacecraft. Each row t/r module phase shifts the transmit pulse to effect the elevation beam-forming, amplifies it and routes the result via a circulator and feed network to the individual radiating elements. See Figure B-13. The received echoes are routed back to the circulator and on to a low noise amplifier, a second phase shifter implementing the receive beam-forming and thence back to the central receiver. Control logic in the T/R module allows the phase shifters to be changed for the different elevation beams.

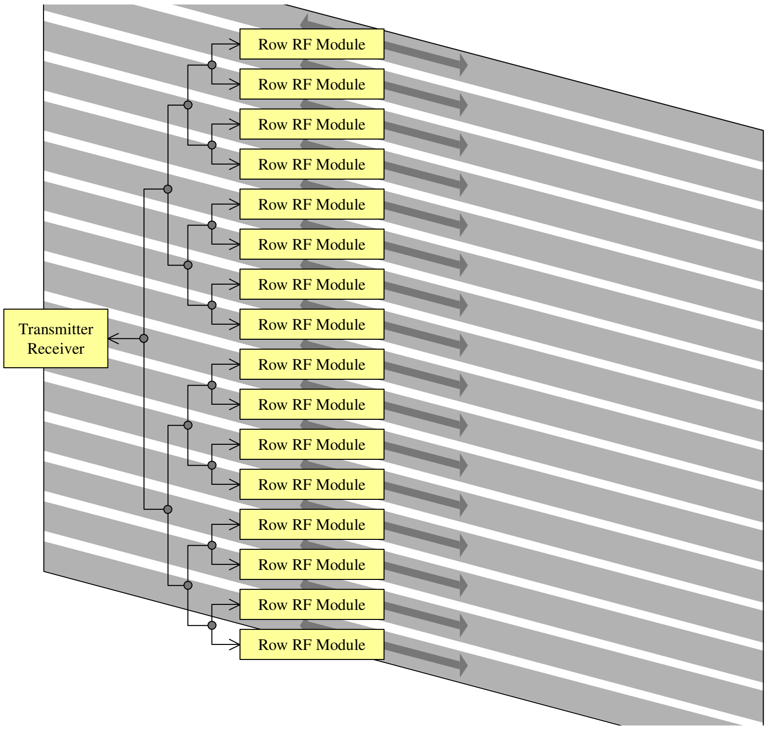

Figure B-12. Row-Based Architecture – Feeds to the Antenna Rows

[23] The other main options are "centralised" and "active". Centralised architectures (c.f. ERS) employ a single very high-power RF amplifier such as a travelling wave tube. A centralised architecture suffers because of the long RF path length and high losses after the HPA, and needs massive high power phase shifters if elevation steering is required. An active architecture (c.f. ASAR) uses a large number of small transmit/receive modules distributed over the entire array. This approach is good with regard to losses and allows electronic steering in two dimensions if required, but the combined mass of all the t/r modules is generally prohibitive. The row-based architecture is a useful compromise between these two extremes.

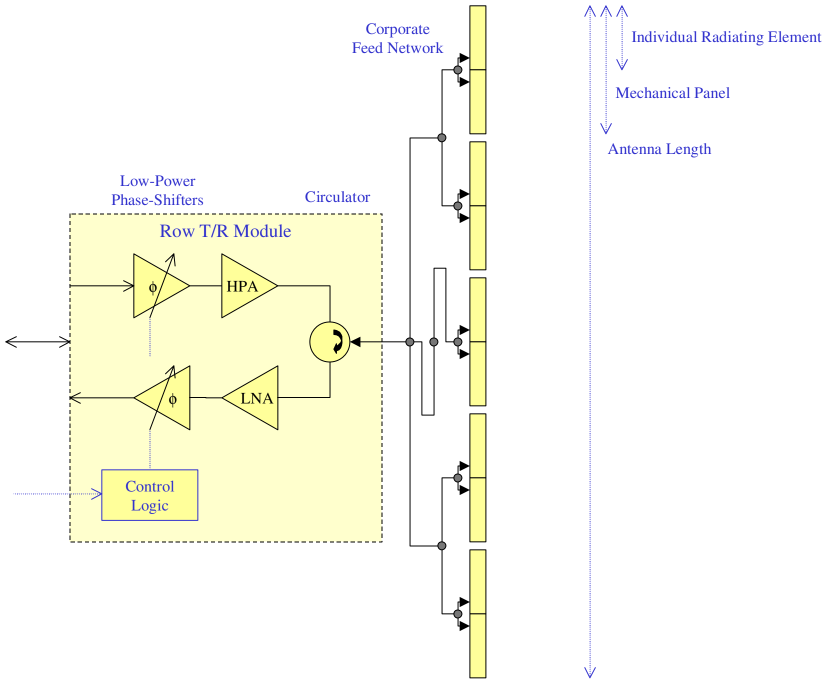

Figure B-13. Row-Based Architecture – Distribution within each Row

Advantages of the row-based architecture compared to a centralised architecture are that the phase-shifters operate at low power, so can be small, and the HPA and LNA are quite close to the radiating elements, so losses are low. Compared to a fully active architecture, there are far fewer t/r modules and their total mass is generally less. Also, the t/r modules are not distributed over the entire antenna and so much less mechanical support is required.

- **Antenna:** At 7 m by 1 m, the antenna is uncomfortably large and would need to be folded for launch. For X-band operation, the mechanical tolerances are tight (~ 1 mm) and adequate mechanical rigidity needs to be designed in.

  If a row-based architecture is assumed (see above), the antenna itself is passive and thereby significantly simplified. Slotted wave-guide or patch radiators might be used at X-band. For space-borne SAR, the former are typically used because the wave-guide structure also contributes substantially to the mechanical rigidity. Wave-guide radiators constructed of CFRP with a thin metallic coating can have low mass, of the order of 5–10 kg/m² or therefore 35–70 kg for a 7 m² antenna. The feed network might comprise about 12 m of metallised CFRP wave-guide per antenna row or 600 m for all 50 rows, which at 50–100 g/m amounts to a further 30–60 kg. Allowing another 50% for the mechanical structure (including deployment mechanisms etc.) implies a total antenna mass of 100–200 kg.

- **Power:** The peak RF power was taken as 4 kW. For a 30 µs pulse duration and a PRF of ~ 2250 Hz, see Table B-1 and Table B-2, the duty cycle is ~ 7 % and the average RF power generated is ~ 270 W. Assuming an overall RF power conversion efficiency of 20–25 % and some additional power consumption for the other electronics, the electrical power demand is of the order of 1.5 kW average (during radar operations). Thus, very large batteries and solar arrays (and carefully designed heat dissipation) would be required if the SAR were to be operated continuously over the oceans.

Regarding the RF power amplifiers, the antenna comprises approximately 50 rows so in a row-based architecture each HPA outputs ~ 80 W RF. This could be achieved using solid-state amplifiers at X-band, although several sub-units in parallel might be required. Including the amplifiers, necessary capacitors and additional electronics plus packaging, each t/r module might weigh of the order of 2–4 kg, or 100–200 kg for all 50 or so.

- **Data Handling:** The average raw data-rate is of the order of 40 Mbit/s, see Table B-2. This would amount to about 211 Gbyte/day if the SAR were operated half-time. Given say 50 minutes/day down-link time to a single ground-station, the down-link rate would have to be about 576 Mbit/s. More plausibly, at least six well-separated, high-data-rate ground-stations would be required.

  The mass memory requirement to store, say, three orbits worth of data at 50% operational duty cycle is about 44 Gbyte, implying significant mass and power consumption. Based on the current 2 Gbit memory chips planned for Beagle-2, which consume 1 W/Gbyte in stand-by mode [23], the mass memory would involve an additional power load of the order of 50 W.

  The on-board storage and down-link rates/volumes could be reduced by on-board SAR processing. However, this would require additional hardware, power consumption and development costs.

Adding notional values for other subsystems gives totals masses and powers as in Table B-3.

	Mass (kg)	*Power Load (W)*
Antenna (incl. mechanical aspects)	100–200	
T/R Modules	100–200	1500
Mass Memory	10	50
Other RF Electronics	20	20
Downlink[24]	20	10
Solar Array[25]	50	
Batteries[26]	10	
Total	~ 300–500 kg	~ 1600 W (peak)

Table B-3. Payload Mass and Power Summary

B.5 POSSIBLE TRADE-OFFS

The design of a SAR instrument involves a complicated set of design trade-offs. The particular concept elaborated above was not intended to be ambitious, but still results in a relatively large payload. Thus it is appropriate to consider further design trade-offs with a view to reducing the instrument size and, generally therefore, capabilities.

[24] Assuming a steered small down-link at X-band or Ka-band; a broadcast downlink would have to be much larger / more powerful to achieve the same link budget.

[25] Sized to provide 2000 W, assuming ~ 40 W/kg for current-technology rigid solar arrays [24].

[26] Sized to provide 2000 W h (= 2000 W × 0.25 h / 25% depth-of-discharge), assuming ~ 100 W h/kg for current Lithium-ion batteries [24].

Key trade-offs that might be considered are as follows:

Design Change	*Impacts, positive and negative*
Increase frequency f	☺ Reduces antenna area for same ambiguity levels ($\propto \sim 1/f$) ☹ Decreases signal-to-noise ($\propto 1/f$) ☹ Tightens antenna mechanical tolerances ☹ Increases susceptibility to interference from rain etc.
Increase pulse bandwidth B_p	☺ Improves range resolution ($\rho_r \propto 1/B_p$) *or* increases number of range looks at constant resolution ($\propto 1/B_p$) ☹ Increases data rate and volume ($\propto B_p$) ☹ Decreases signal-to-noise ratio ($\propto 1/B_p$)
Increase pulse length T_p	☺ Reduces peak power for given SNR ($\propto T_p$) 😐 Does not change average power for given SNR
Limit maximum elevation θ_{max}	☺ Reduces antenna area for same ambiguity levels ($\propto \sim \tan\theta_{max}$) ☺ Reduces data rate *or* allows more Doppler looks ☹ Reduces the swath width ($\propto \sim \tan\theta_{max} - \tan\theta_{min}$)
Change antenna aspect ratio	😐 Changes balance between range and azimuth ambiguities 😐 Changes mechanical deployment and stowage issues

Table B-4. Main Trade-Offs for a Synthetic Aperture Radar